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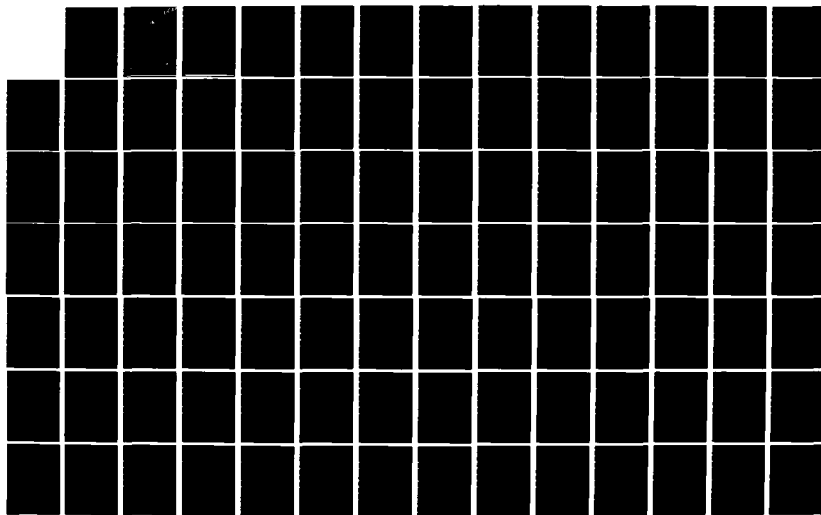
FREQUENCY RESPONSE OF HYDRAULIC TRANSMISSION LINES(U)  
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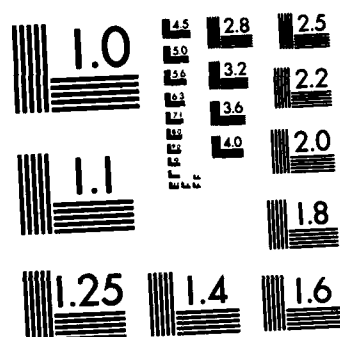
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REPORT NO. NADC-80252-60



## FREQUENCY RESPONSE OF HYDRAULIC TRANSMISSION LINES

Robert L. Woods and Jack Chung  
Fluid Controls Center for  
Research and Development  
The University of Texas at Arlington  
Arlington, Texas 76019

25 MAY 1982

FINAL REPORT

*Approved for Public Release; Distribution Unlimited*

Prepared For  
NAVAL AIR DEVELOPMENT CENTER  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) — This report investigates the correlation between theory and experiment for hydraulic transmission lines used to transmit pressure signals over long distances in fluidic control circuits. Typical source and load impedances connected to the lines are considered. A vast amount of experimental data is presented for various line lengths and diameters connected to different source and load impedances. The agreement is excellent for the "exact" distributed parameter theory. <—		

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PREFACE

This work was conducted by the Fluid Controls Center of The University of Texas at Arlington for the Naval Air Development Center in response to agreement #N62269-81-M-3056. Dr. Robert L. Woods served as the principal investigator and Mr. Jack Chung and Mr. C. H. Hsu collected the experimental data. Miss S. K. O'Grady typed the report.

This work was performed for Mr. David Keyser at NADC, and Mr. Dean Houck at NAVAIR, in support of the Navy's effort in fluidic backup flight controls.

The reason for this effort was to collect a data base for the experimental response of hydraulic lines and to verify which theoretical models to use. The literature in the area is lacking the combined effects of source and load impedances and capacitances. These are a primary concern for practical fluidic control circuits driving realistic loads.

The results presented here are very satisfying since they exactly conform to the theoretical model. With this verification, extrapolation to other situations can be made with confidence.

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TABLE OF CONTENTS

1.	Introduction and Background . . . . .	5
2.	Fluid Transmission Line Theory . . . . .	7
3.	Typical Experimental Responses . . . . .	11
3.1	Blocked Lines . . . . .	11
3.2	Load Impedances . . . . .	11
3.3	Source Impedances . . . . .	25
3.4	Load and Source Impedances . . . . .	35
4.	Summary and Conclusions . . . . .	55
	References . . . . .	57
	Appendix A. Experimental Data . . . . .	59
	Nomenclature and Notation . . . . .	231

## 1. INTRODUCTION AND BACKGROUND

Fluid transmission lines can be used to transmit fluid pressure signals over relatively long distances in a variety of applications of interest to the Navy. Of particular interest is the application in fluidic flight control systems for aircraft or missiles. A current issue is the fluidic flight control system that would serve as a backup to a digital fly-by-wire system in advanced Naval aircraft [1-3]<sup>1</sup>.

Previous studies [3,4] have compared theoretical models with experimental responses for pneumatic transmission lines. These studies have shown excellent agreement between theory and experiment. It has also been shown [4] that two fluid transmission lines transmitting a differential pressure signal (typical of fluidic systems) behave as a single line.

The purpose of this investigation is to test the frequency response of typical lines using MIL-H-5606 hydraulic fluid and to compare the results to the exact distributed-parameter model. This investigation includes lines with a blocked load, lines with resistive and resistive plus inductive loads, as well as lines with a source impedance. The results presented confirm that the distributed-parameter models are required to accurately describe the response. It was found that models for load and source resistances must include inductance under some conditions even though the length of the resistance tubing is small compared to the line length. However, when the correct mathematical models are used, the theory and experiment are in good agreement.

<sup>1</sup>Numbers in brackets designate references in the list of references.

2. FLUID TRANSMISSION LINE THEORY

Fluid lines used to transmit fluidic signals from one location to another must be modeled considering the distributed-parameter nature of the effects. The resulting line model [4,5] is infinite-ordered and can be expressed in terms of hyperbolic trigonometric functions and complex Bessel functions.

$$\delta P_b = \frac{1}{\cosh \Gamma} \delta P_a - \frac{Z_c \sinh \Gamma}{\cosh \Gamma} Q_b \quad (1)$$

$$Q_a = \frac{\sinh \Gamma}{Z_c \cosh \Gamma} \delta P_a + \frac{1}{\cosh \Gamma} Q_b \quad (2)$$

Where  $\delta P_a$  and  $\delta P_b$  are the gauge pressures at the inlet and outlet of the line and  $Q_a$  and  $Q_b$  are the volumetric flow rate.

The propagation operator,  $\Gamma$ , is a sort of normalized derivative that is related to the signal transport time.

$$\Gamma = \bar{D}_c \left[ \frac{1 + (\gamma - 1) B_r(\sigma \bar{D}_v)}{1 - B_r(\bar{D}_v)} \right]^{1/2} \quad (3)$$

However, for oil,  $\gamma = 1.0$ ; therefore the propagation operator simplifies to

$$\Gamma = \bar{D}_c \left[ \frac{1}{1 - B_r(\bar{D}_v)} \right]^{1/2} \quad (\text{for oil}) \quad (4)$$

where

$$\bar{D}_c = \frac{D}{\omega_c} \quad (5)$$

$$\omega_c = \text{line characteristic frequency} = \frac{c_o}{l} \quad (6)$$

$$\bar{D}_v = \frac{D}{\omega_v} \quad (7)$$

$$\omega_v = \text{line viscous frequency} = \frac{32\nu}{d^2} \quad (8)$$

$$B_r(\bar{D}_v) = \text{ratio of Bessel functions} = \frac{2 J_1(j\sqrt{8 \bar{D}_v})}{j\sqrt{8 \bar{D}_v} J_0(j\sqrt{8 \bar{D}_v})} \quad (9)$$

By the use of the polynomial forms of Bessel functions,  $B_r$  can be expressed as the following.

$$B_r(\bar{D}_v) = \frac{\sum_{m=0}^n (a_m \bar{D}_v)^m}{\sum_{m=0}^n (b_m \bar{D}_v)^m} \quad (10)$$

Where

$$a_m = \frac{2}{\sqrt{(m!)^2 (m+1)}} \quad (11)$$

$$b_m = \frac{2}{\sqrt{(m!)^2}} \quad (12)$$

The maximum number of terms required in the expansion,  $n$ , depends upon the maximum frequency of interest and the viscous frequency.

$$n = 2.59 \left[ \frac{\omega_{\max}}{\omega_v} \right]^{1/2} \quad (13)$$

The Bessel function ratio becomes a complex number when sinusoidal excitation is considered ( $D = j\omega$ ). At low frequency the Bessel function ratio is equal to 1.0 and is real; at high frequency, it approaches zero in magnitude with a 45° phase lag.

The line characteristic impedance is a function of the Bessel function ratio.

$$Z_c = Z_o \left[ \frac{1}{\{1 + (\gamma - 1) B_r(\sigma \bar{D}_v)\} \{1 - B_r(\bar{D}_v)\}} \right]^{1/2} \quad (14)$$

Where

$$Z_o = \text{Line impedance constant} = \frac{4 \rho c_o}{\pi d^2} \quad (15)$$

Considering that  $\gamma \approx 1$  for oil,  $Z_c$  reduces to the following.

$$Z_c = Z_o \left[ \frac{1}{1 - B_r(\bar{D}_v)} \right]^{1/2} \quad (16)$$

At low frequencies,  $Z_c$  has  $45^\circ$  phase lag and a large magnitude that decreases to  $Z_o$  (with zero phase) at high frequency.

Even though two normalization factors,  $\omega_c$  and  $\omega_v$ , are used in the preceding equations, it is more meaningful to use the characteristic frequency,  $\omega_c$  and the damping ratio,  $\zeta$ , to characterize the response of lumped-parameter line model.

$$\zeta = 16 \frac{v}{c_o} \frac{l}{d^2} \quad (17)$$

Thus

$$\omega_v = 2 \zeta \omega_c \quad (18)$$

The normalized frequency,  $\omega/\omega_c$ , and the damping ratio,  $\zeta$ , is used in the remainder of this report as the characteristic parameters of lines. Most authors use the propagation number,  $P_n$ , and the dissipation number,  $D_n$ , to characterize the line. The two sets of parameters are related as follows.

$$P_n = \frac{\omega}{\frac{\pi}{2} \omega_c} \quad (19)$$

$$D_n = \frac{\zeta}{4} \quad (20)$$

Figure 1 illustrates the frequency response of a hydraulic transmission line with an infinite load impedance (blocked termination). Notice that the line exhibits multiple resonances characteristic of infinite-ordered systems. The undamped resonant frequencies occur at odd multiples of  $\omega/\omega_c = \pi/2$ . The amplitude of resonance is determined by the damping; the response for  $\zeta = 1.0$  is almost flat thereby giving some physical feeling to the concept of critical damping.

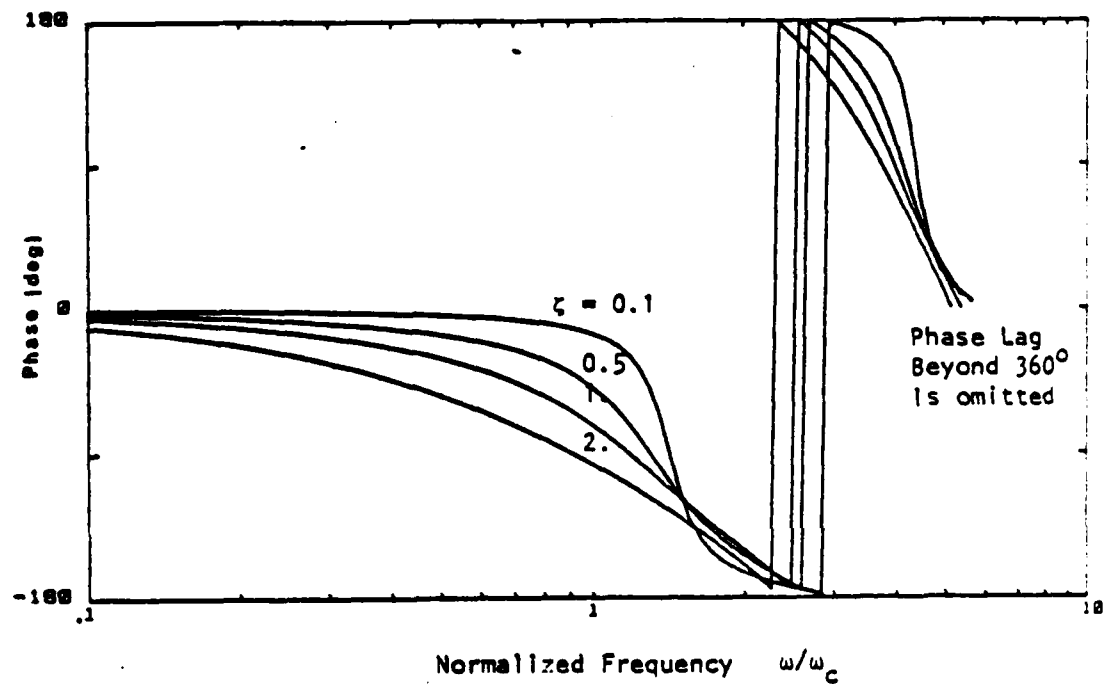
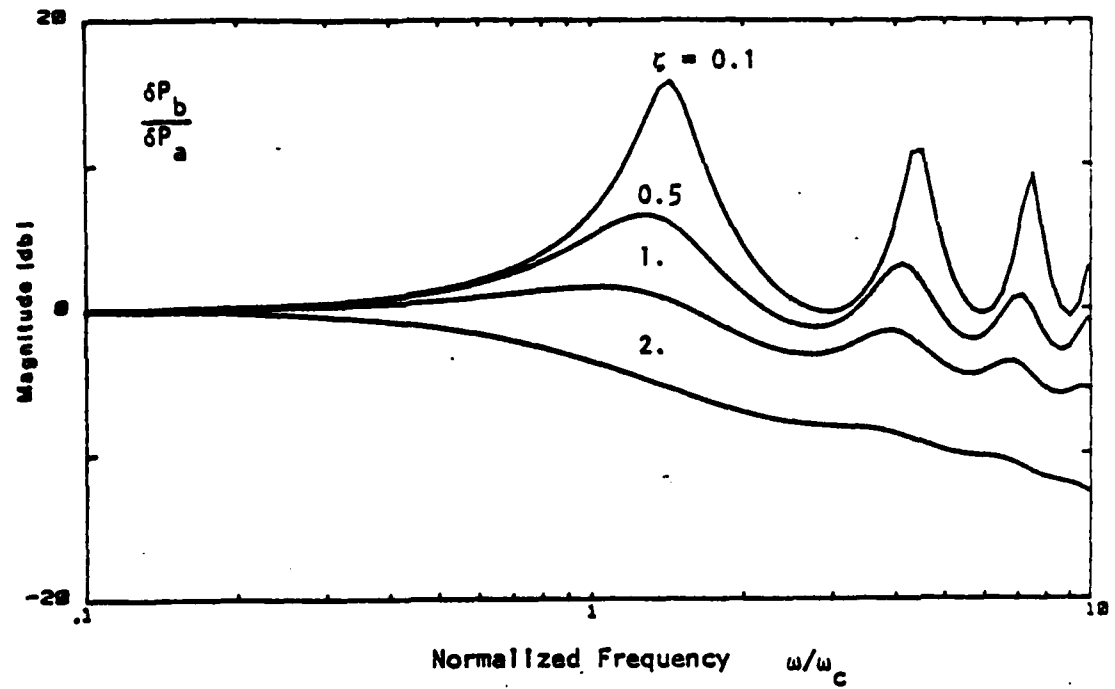


Fig 1 Frequency Response of Hydraulic Transmission Line with Various Damping (Theoretical, Infinite Load Impedance)

### 3. TYPICAL EXPERIMENTAL RESPONSES

A wide variety of lines with source and/or load impedances have been tested with details presented more fully in Appendix A. The important concepts and effects are presented here.

#### 3.1 BLOCKED LINES

For a blocked line, the terminal condition is simply represented by  $Q_b = 0$ . Combining this equation with the transmission line model (equations 1 and 2) results in the following transfer function.

$$\delta P_b = \frac{1}{\cosh \Gamma} \delta P_a \quad (21)$$

Figures 2, 3, and 4 show theoretical responses for three different diameter lines compared to the experimental results; some deviation between theory and experiment can be noted. This is due to the following two factors:

- 1). The parasitic capacitance in the transducer manifold and the transducer cannot be neglected for small diameter lines (volume = 1.3 mm<sup>3</sup>, capacitance = 1 pf).
- 2). The effective line viscosity shows the tendency to increase with line diameter. This phenomenon needs further study in the future. For the present, it has been determined that for the 4.8 mm diameter line, the effective line viscosity is 1.5 of the nominal, and for the 7.6 mm diameter line, it is 2.5 times the nominal.

Figures 5, 6, and 7 show the response after accounting for parasitic capacitance and effective line viscosity. Very good agreement between theory and experiment can be noted.

#### 3.2 LOAD IMPEDANCE

The connection of the output of a line to a capillary tube or input ports to a fluid amplifier results in resistive termination. The model for a pure load resistance is given below:

$$\delta P_b = R_L Q_b \quad (22)$$

Combining this equation with the transmission line model (equations 1 and 2) results in the following transfer function.

$$\delta P_b = \frac{1}{\cosh \Gamma + \frac{Z_c}{R_L} \sinh \Gamma} \quad (23)$$

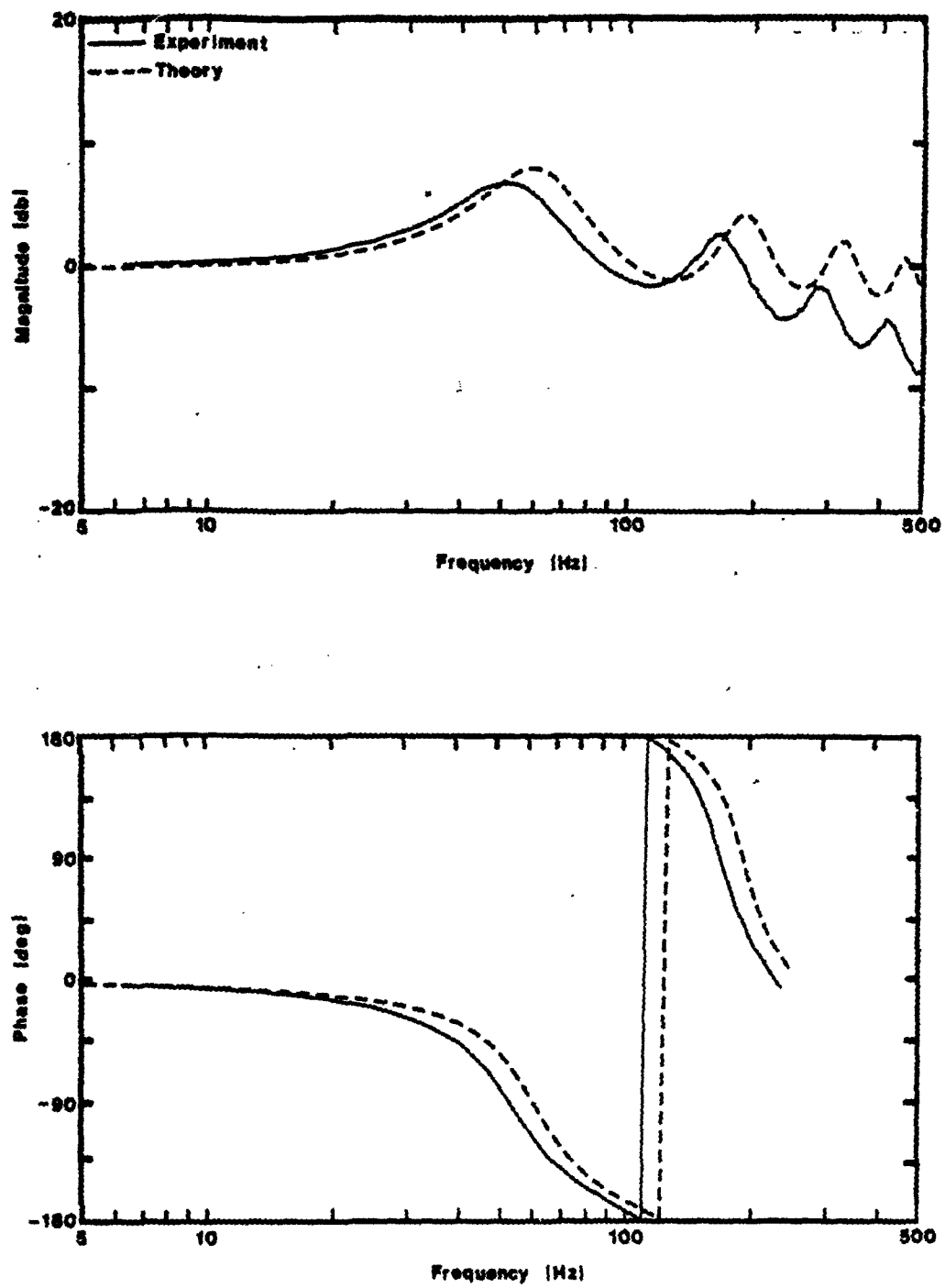


Fig 2. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ , blocked)

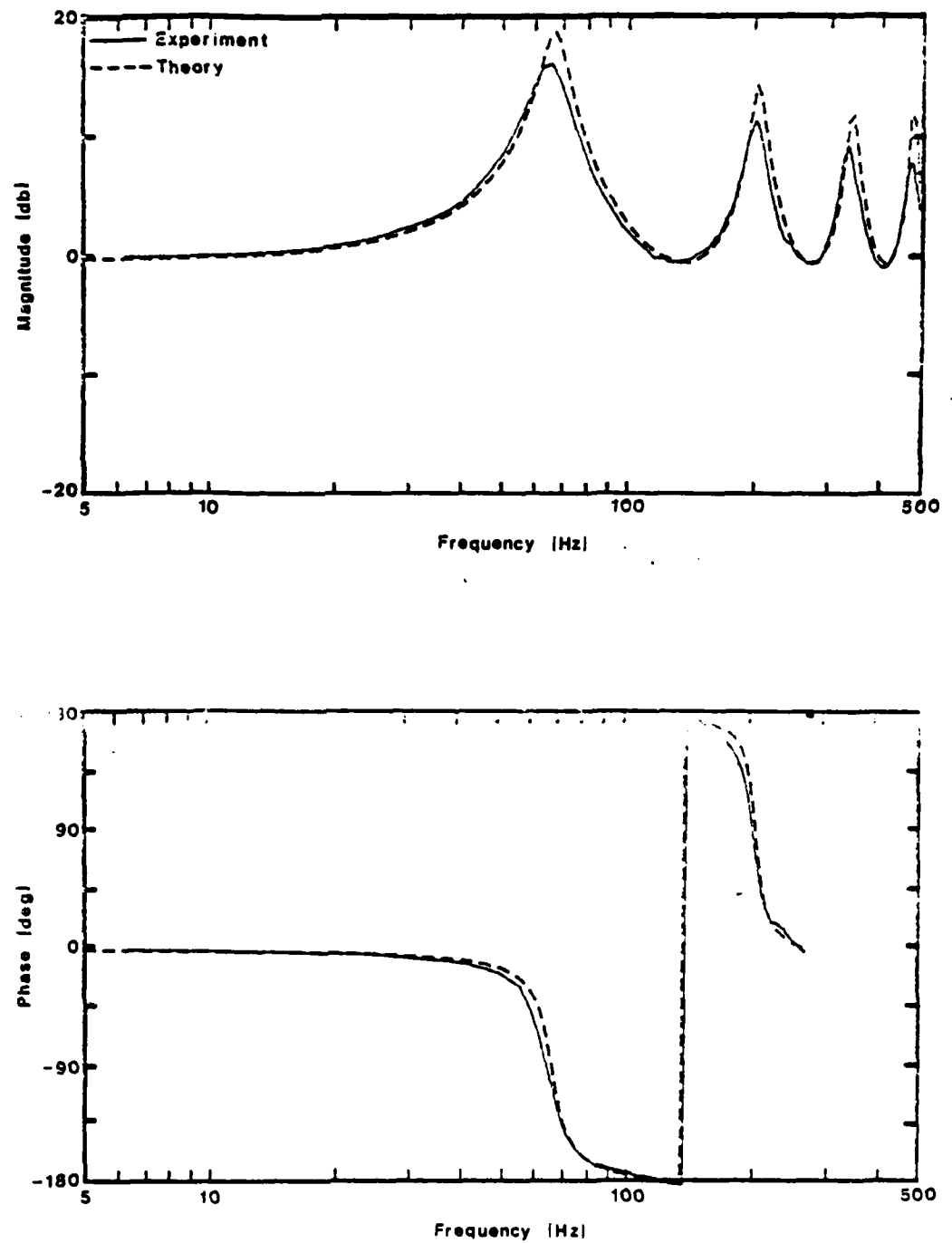


Fig 3. Frequency Response of Hydraulic Transmission Line  
( $\lambda = 4.8\text{m}$ ,  $d = 4.9\text{mm}$ , blocked)

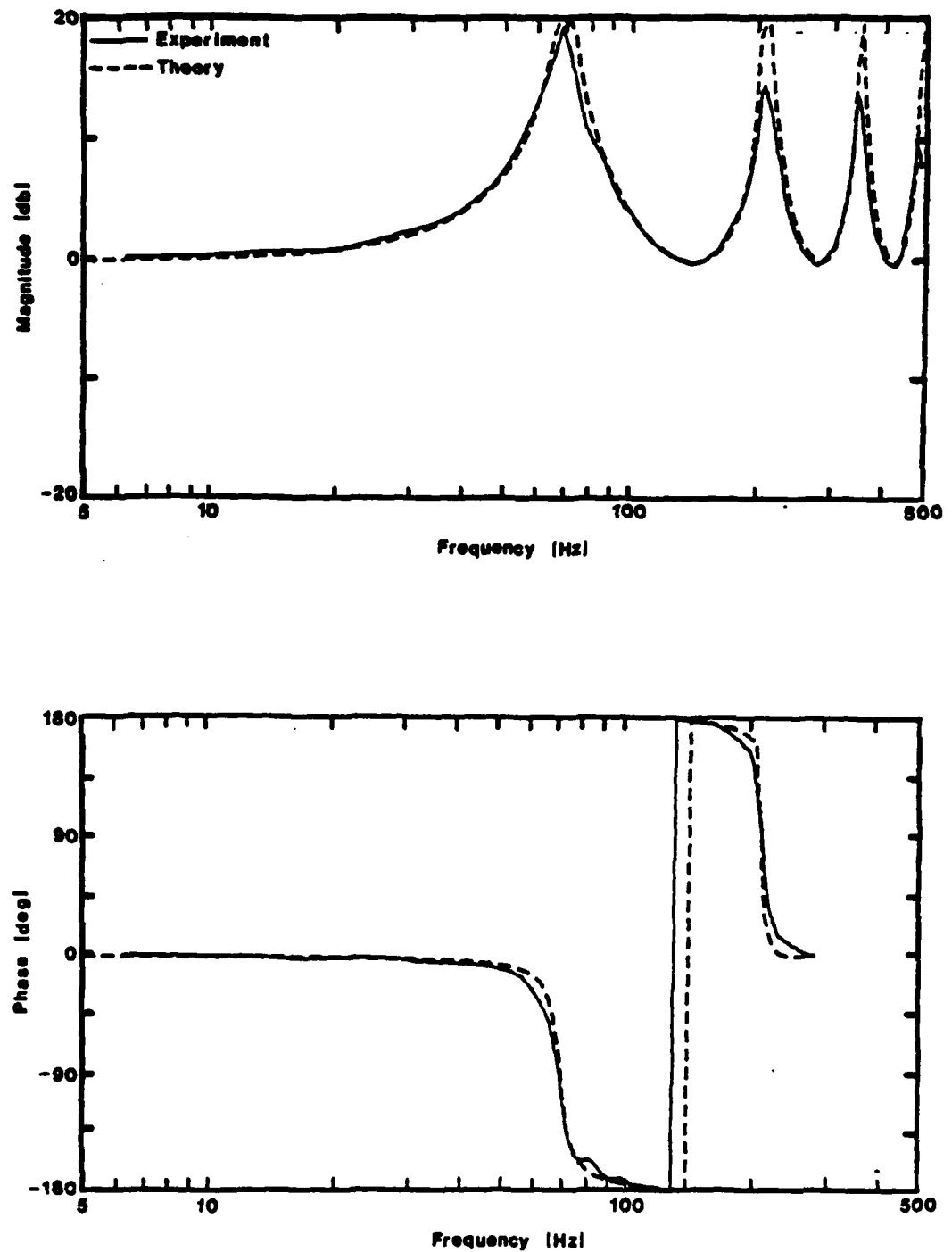


Fig 4. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ , blocked)

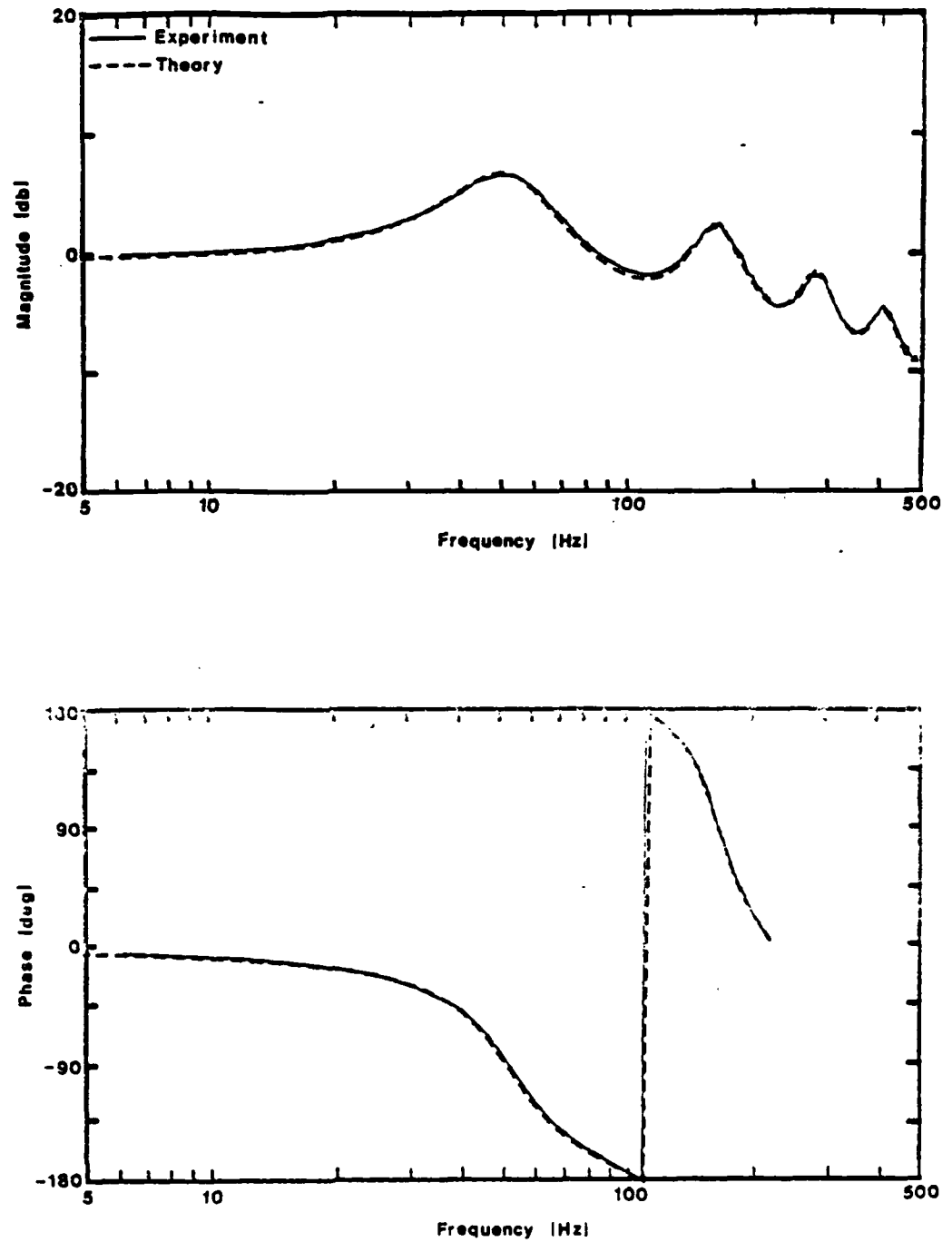


Fig 5. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ,  $C_L = 1\text{pf}$ )

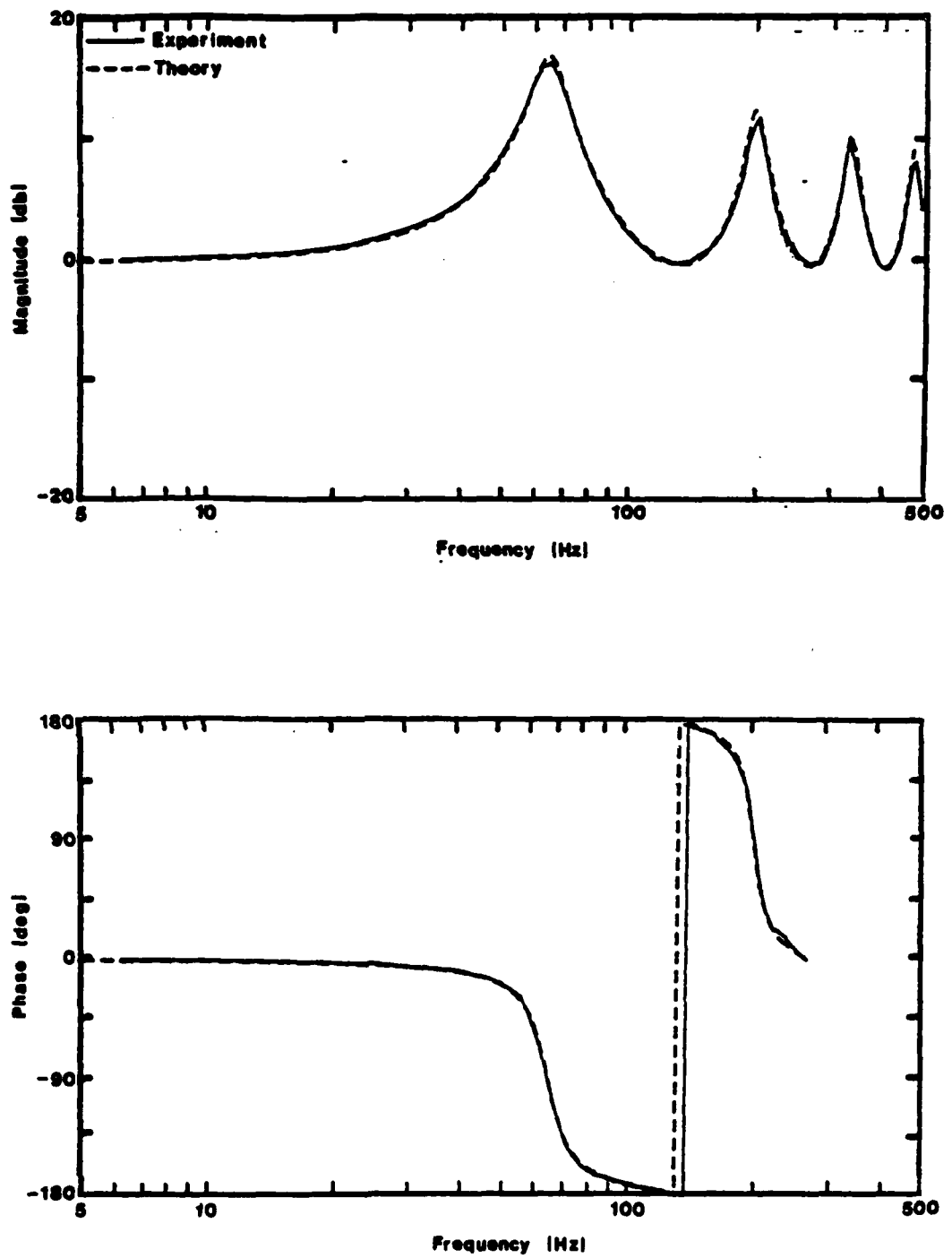


Fig 6. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ,  $C_L = 1\text{pf}$ )

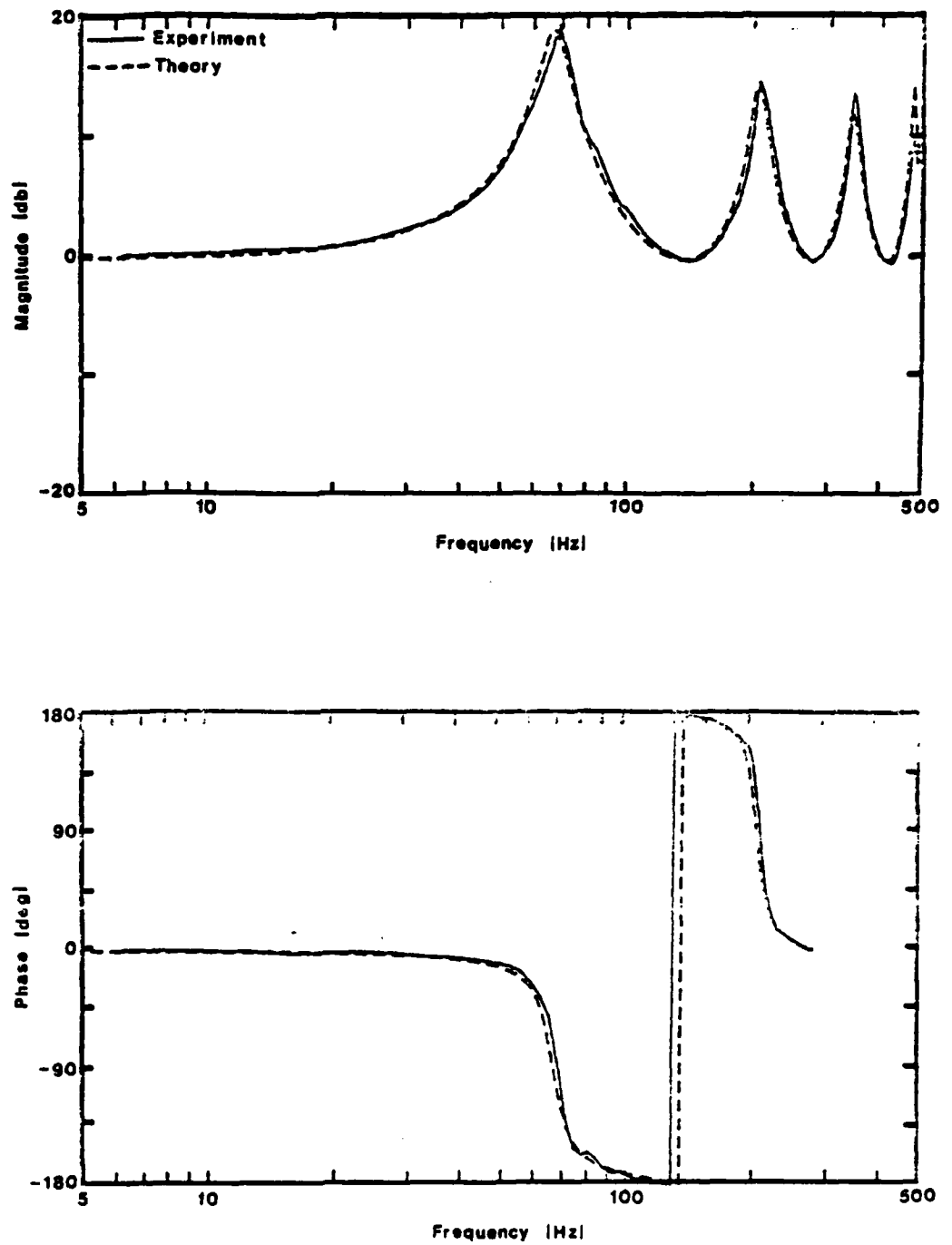


Fig 7. Frequency Response of Hydraulic Transmission Line  
( $\lambda = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ,  $C_L = 1\text{pF}$ )

The blocked-load line termination case is represented by  $R_L = \infty$ . As can be seen with  $R_L = \infty$ , the transfer function reduces to the  $\cosh \Gamma$  term. The above equation predicts, that as  $R_L$  reduces to a finite value, the  $\sinh \Gamma$  term will become more significant and eventually will shift the resonant frequency from  $\omega/\omega_c$  being odd multiples of  $\pi/2$  to even multiples of  $\pi/2$  and that there will be an overall attenuation.

Figures 8, 9, and 10 show the comparison between experiment and theory for the resistive load model, the experiments show that for higher frequencies, the magnitude ratio tends to increase to the contrary of the theory. This may seem puzzling at first glance since the first resonant frequency of the capillary tube ( $\omega_{CL} = 4329$  Hz, refer to Appendix A) is above the 500 Hz range, and should not interfere with the response of the line; however, further study shows that it is the viscous frequency ( $\omega_v = 199$  Hz) that is of significance here. For frequencies higher than the viscous frequency, the inductive impedance will dominate and since inductive impedance increases with frequency, therefore for higher frequencies, the response will tend to approach the infinite load response.

The model for load resistance and inductance is given by

$$\delta P_b = (R_L + L_L D) Q_b \quad (24)$$

Combining this equation with the transmission line model results in the following transfer function:

$$\frac{\delta P_b}{\delta P_a} = \frac{1}{\cosh \Gamma + \frac{Z_c}{R_L + L_L D} \sinh \Gamma} \quad (25)$$

Figures 11, 12, and 13 show the comparison of resistance and inductance model with respective experimental results. Much improvement can be noticed, though some deviation still exists.

An even more accurate model would be to consider the capillary tube as a distributed-parameter model line cascaded to the main transmission line. For the main transmission line, we have

$$\delta P_b = \frac{1}{\cosh \Gamma} \delta P_a - \frac{Z_c \sinh \Gamma}{\cosh \Gamma} Q_b \quad (26)$$

$$Q_a = \frac{\sinh \Gamma}{Z_c \cosh \Gamma} \delta P_a + \frac{1}{\cosh \Gamma} Q_b \quad (27)$$

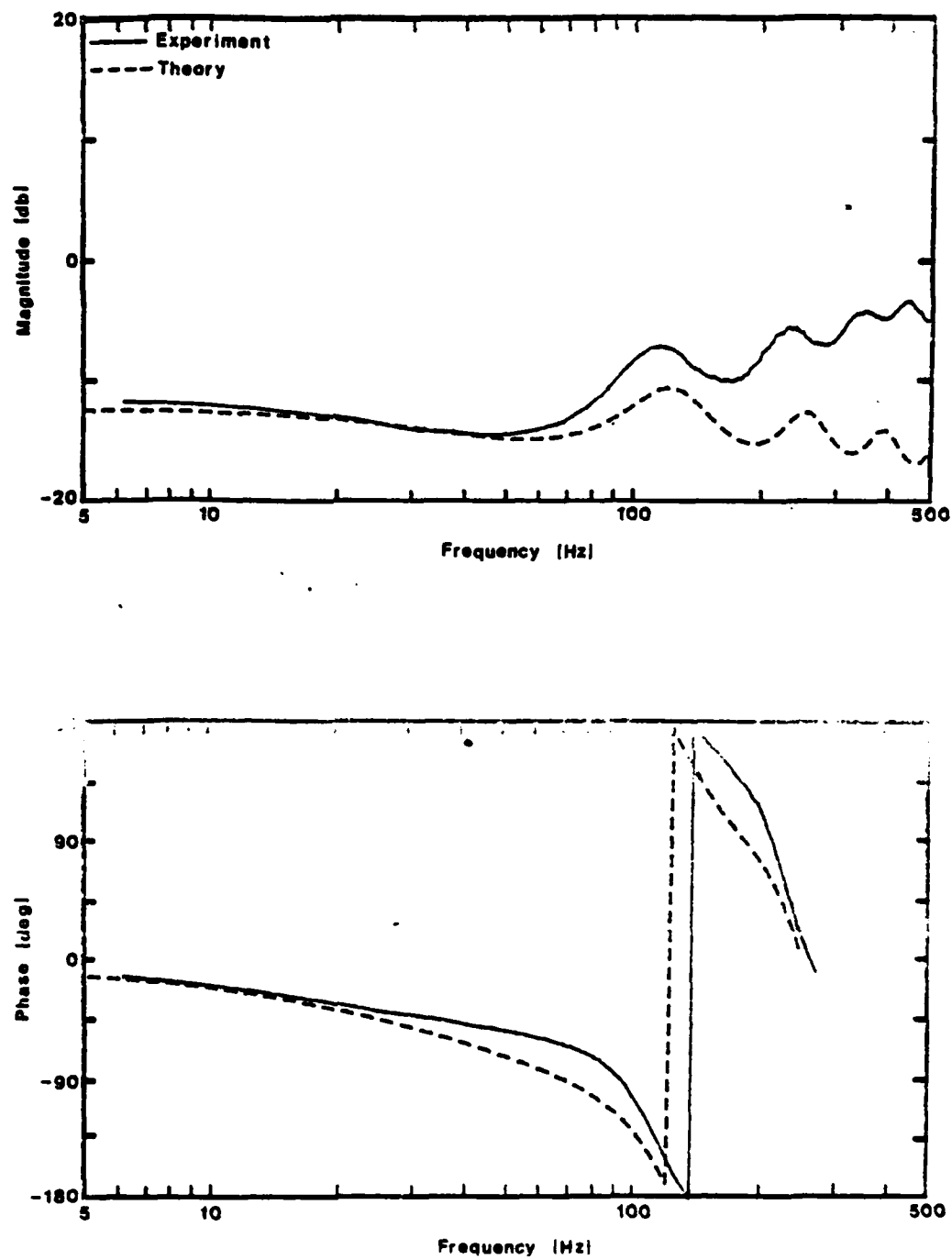


Fig 8. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Load: Resistor #4,  $R_L = 92\text{ M}\Omega$ )

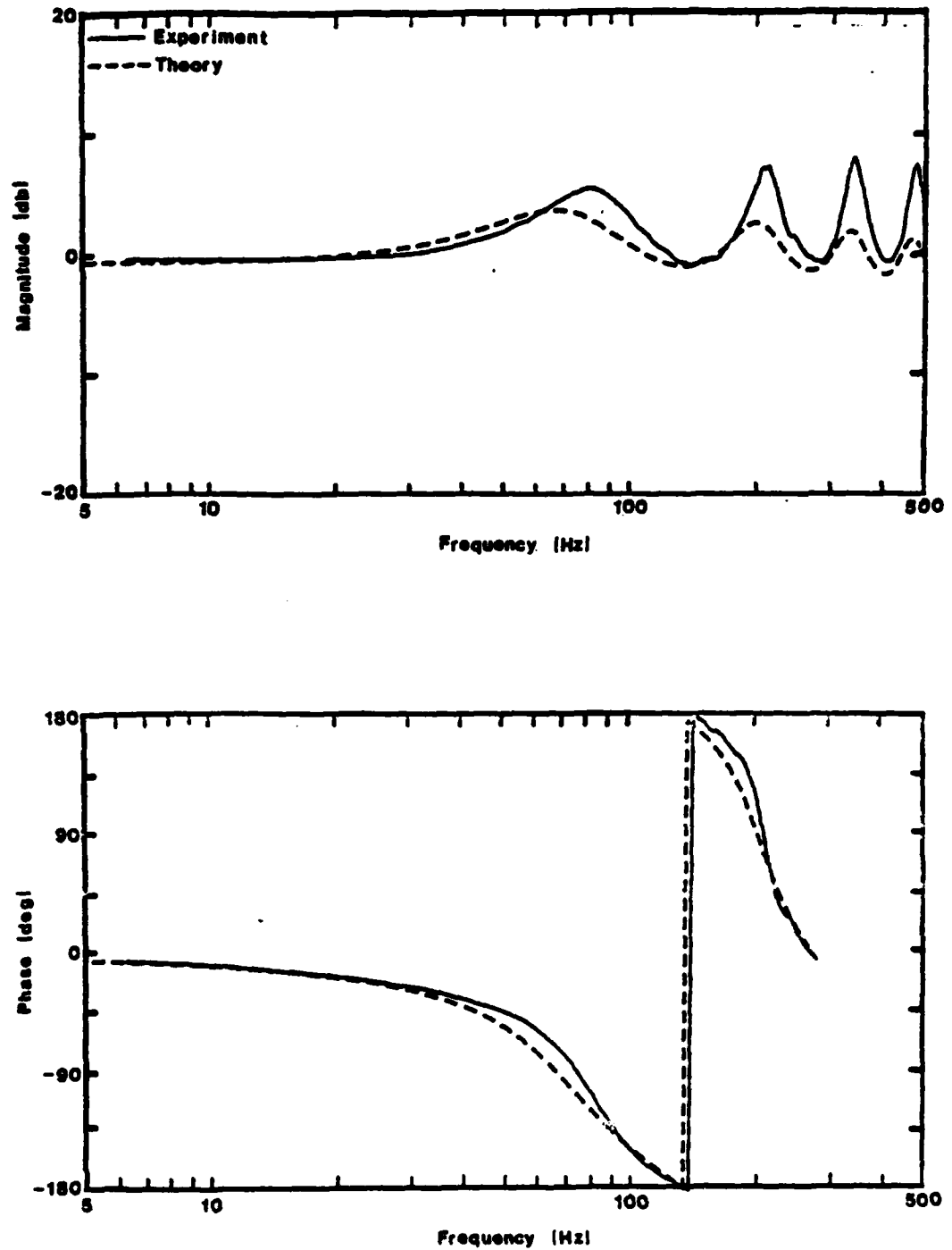


Fig 9. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Load: Resistor #4,  $R_L = 92\text{ M}\Omega$ )

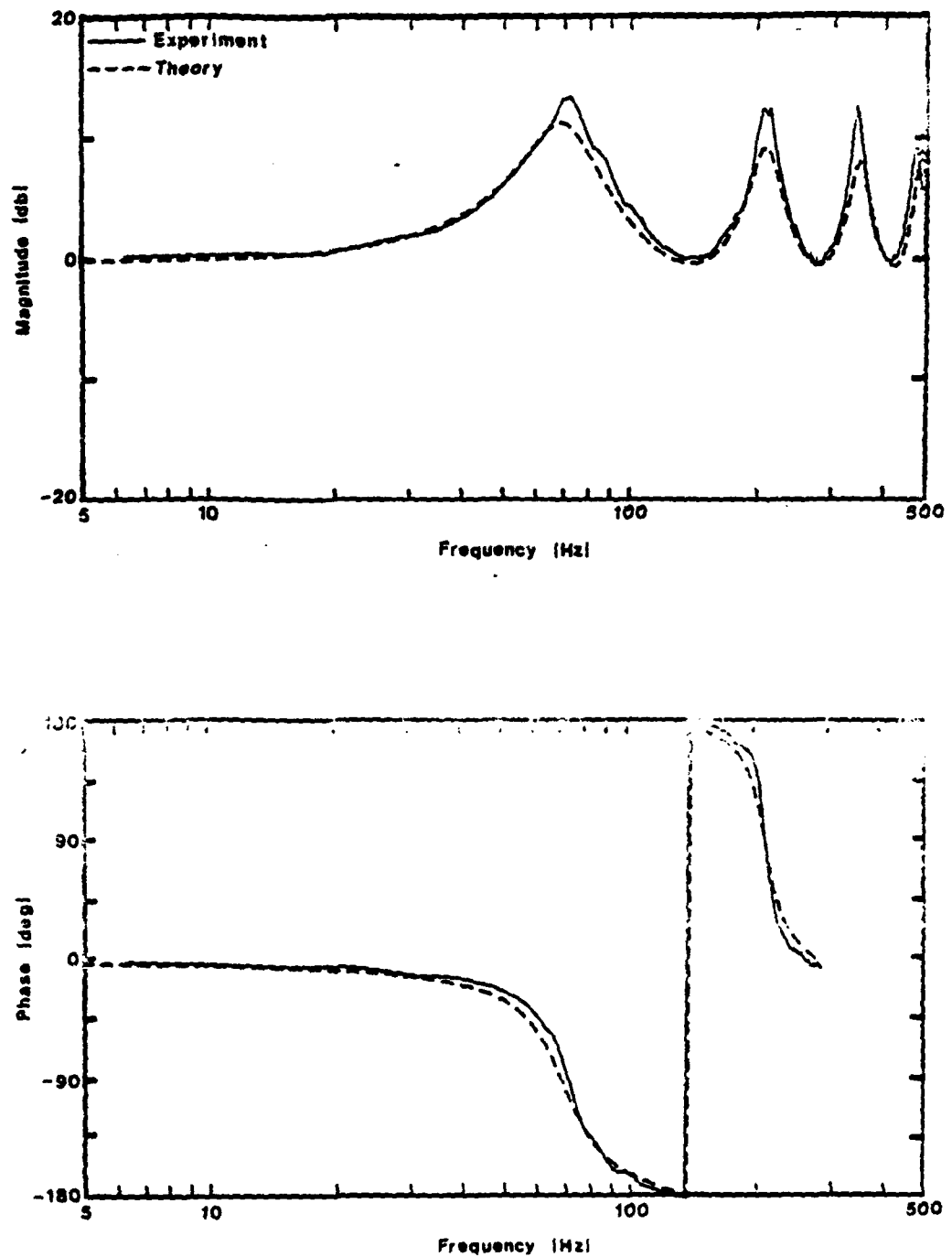


Fig 10. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Load: Resistor #4,  $R_L = 92\text{ M}\Omega$ )

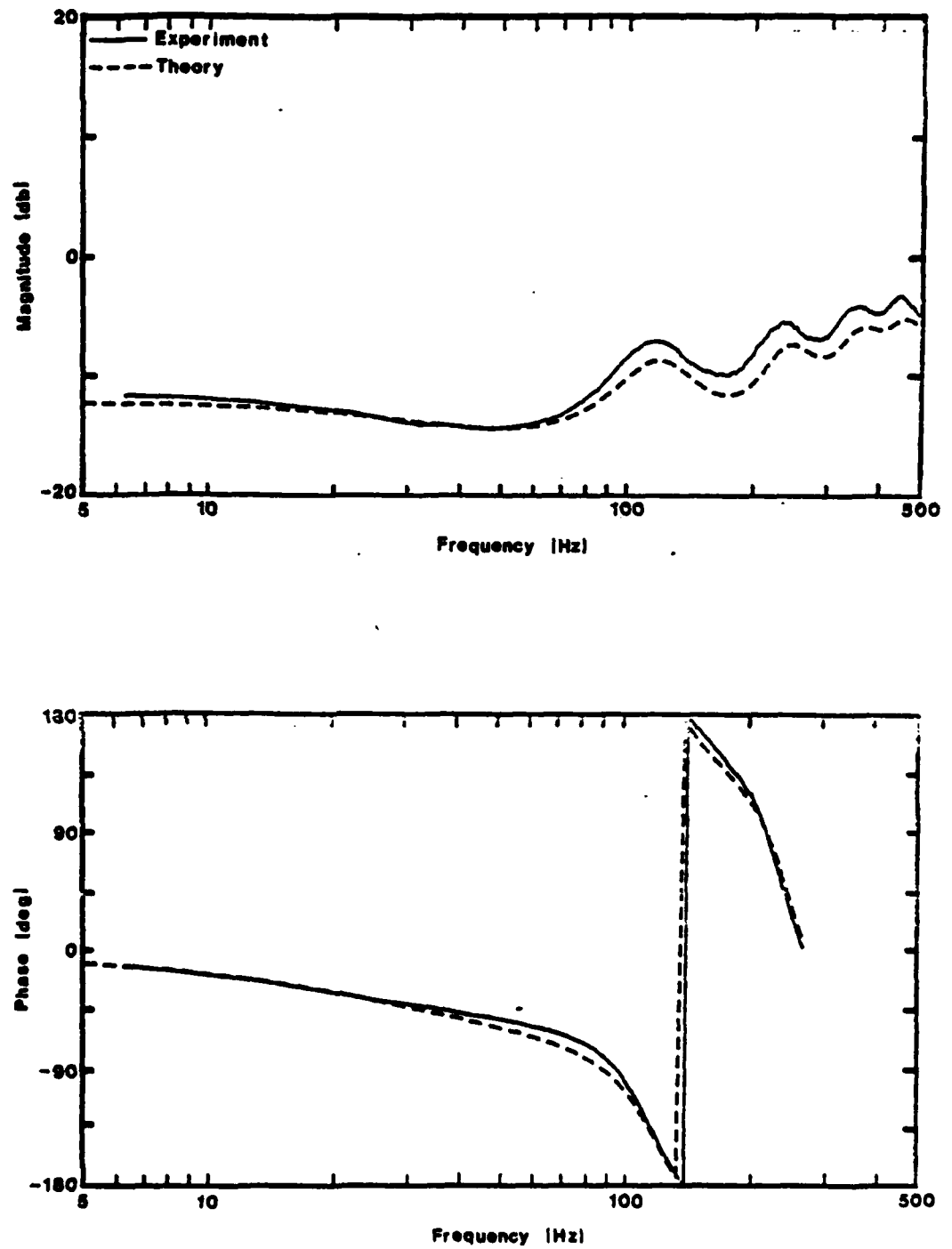


Fig 11. Frequency Response of Hydraulic Transmission Line  
 $\ell = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Load: Resistor #4,  
 $R_L = 92 \text{ M}\Omega$ ,  $L_L = .105 \text{ MHenry}$

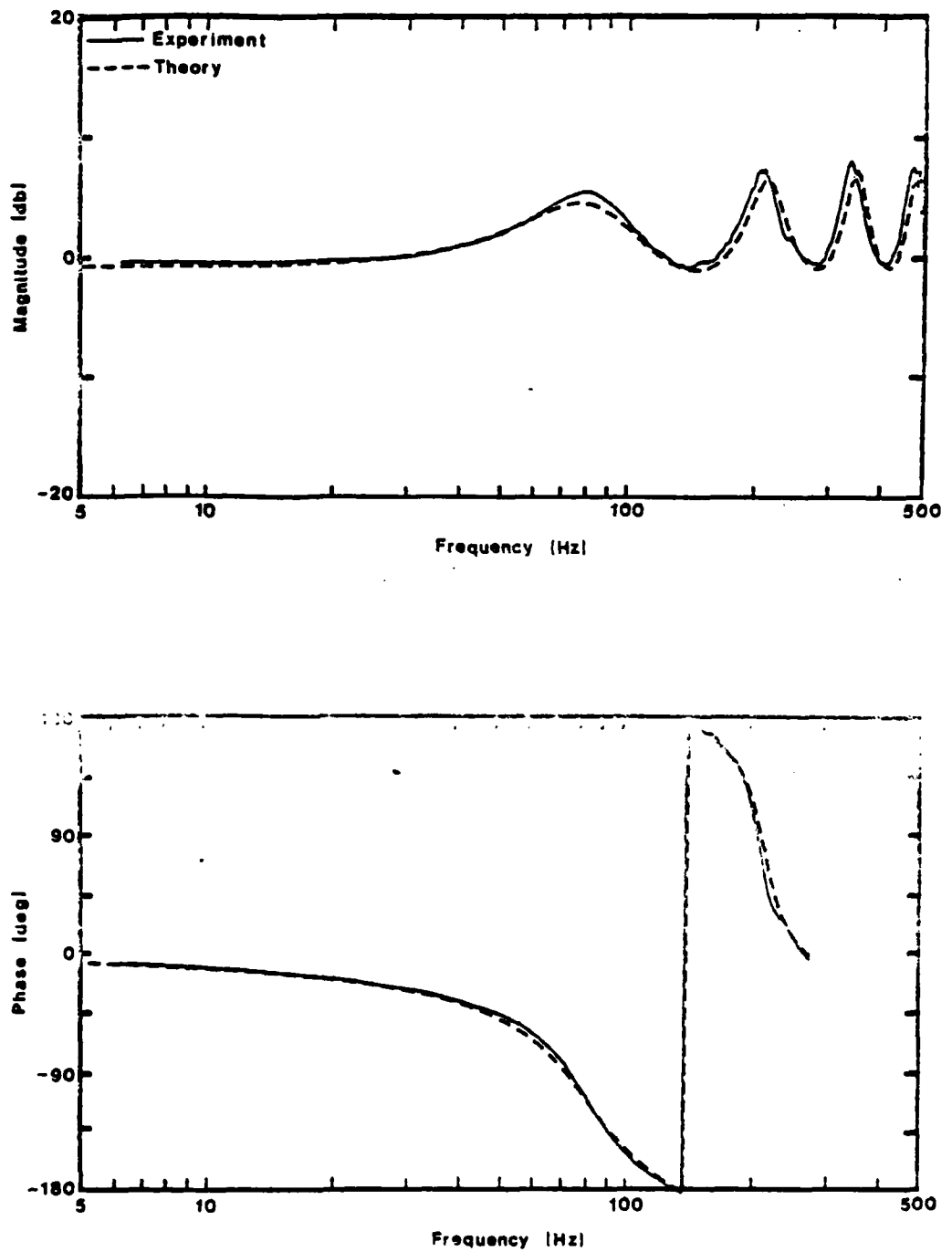


Fig 12. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Load: Resistor #4,  
 $R_L = 92\text{ M}\Omega$ ,  $L_L = .105\text{ mH}$ )

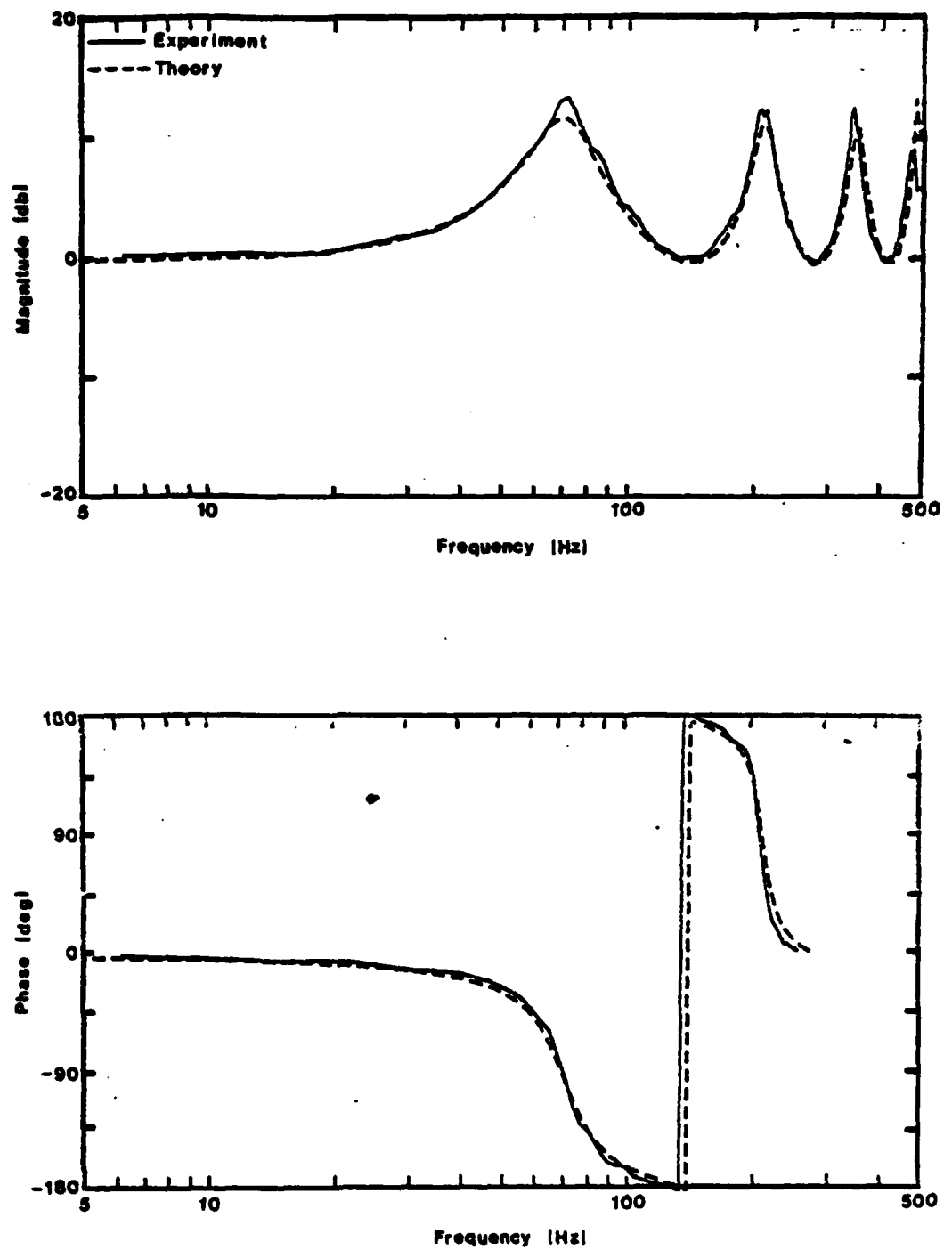


Fig 13. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Load: Resistor #4,  
 $R_L = 92\text{ M}\Omega$ ,  $L_L = .105\text{ MHenry}$ )

For the capillary tube, we have

$$\delta P_{bL} = \frac{1}{\cosh \Gamma_L} \delta P_b - \frac{Z_{CL} \sinh \Gamma_L}{\cosh \Gamma_L} Q_{bL} \quad (28)$$

$$Q_b = \frac{\sinh \Gamma_L}{Z_{CL} \cosh \Gamma_L} \delta P_b + \frac{1}{\cosh \Gamma_L} Q_{bL} \quad (29)$$

With the configuration of the capillary output being grounded ( $\delta P_{bL} = 0$ ), the transfer function with the load line becomes:

$$\frac{\delta P_b}{\delta P_a} = \frac{1}{\cosh \Gamma + \frac{Z_c}{Z_{CL}} \frac{\cosh \Gamma_L}{\sinh \Gamma_L} \sinh \Gamma} \quad (30)$$

Figures 14, 15, and 16 show cascaded-line model with corresponding experimental results. These figures show very good agreement between theory and experiment.

Figures 17, 18, and 19 show experimental responses of lines with different load impedances. Notice that as  $R_L$  is decreased, there is static attenuation and depends on the viscous frequency of the load, the first couple of resonant frequencies will tend to shift to the right; however, for higher frequencies, the response tends to approach the infinite load responses. Another important effect is that the  $-90^\circ$  bandwidth is increased as  $R_L$  is decreased, this is a significant advantage for closed-loop control systems.

### 3.3 SOURCE IMPEDANCES

For ideal source resistance with an infinite load resistance ( $Q_b = 0$ ), the transfer function is:

$$\frac{\delta P_b}{\delta P_s} = \frac{1}{\cosh \Gamma + \frac{R_s}{Z_c} \sinh \Gamma} \quad (31)$$

Figures 20, 21, and 22 show the ideal source resistance model along with the experimental results. Similar to the load resistance case, the inductive effects generally cannot be neglected.

For source resistance and inductance model, the transfer function becomes:

$$\frac{\delta P_b}{\delta P_s} = \frac{1}{\cosh \Gamma + \frac{R_s + L_s D}{Z_c} \sinh \Gamma} \quad (32)$$

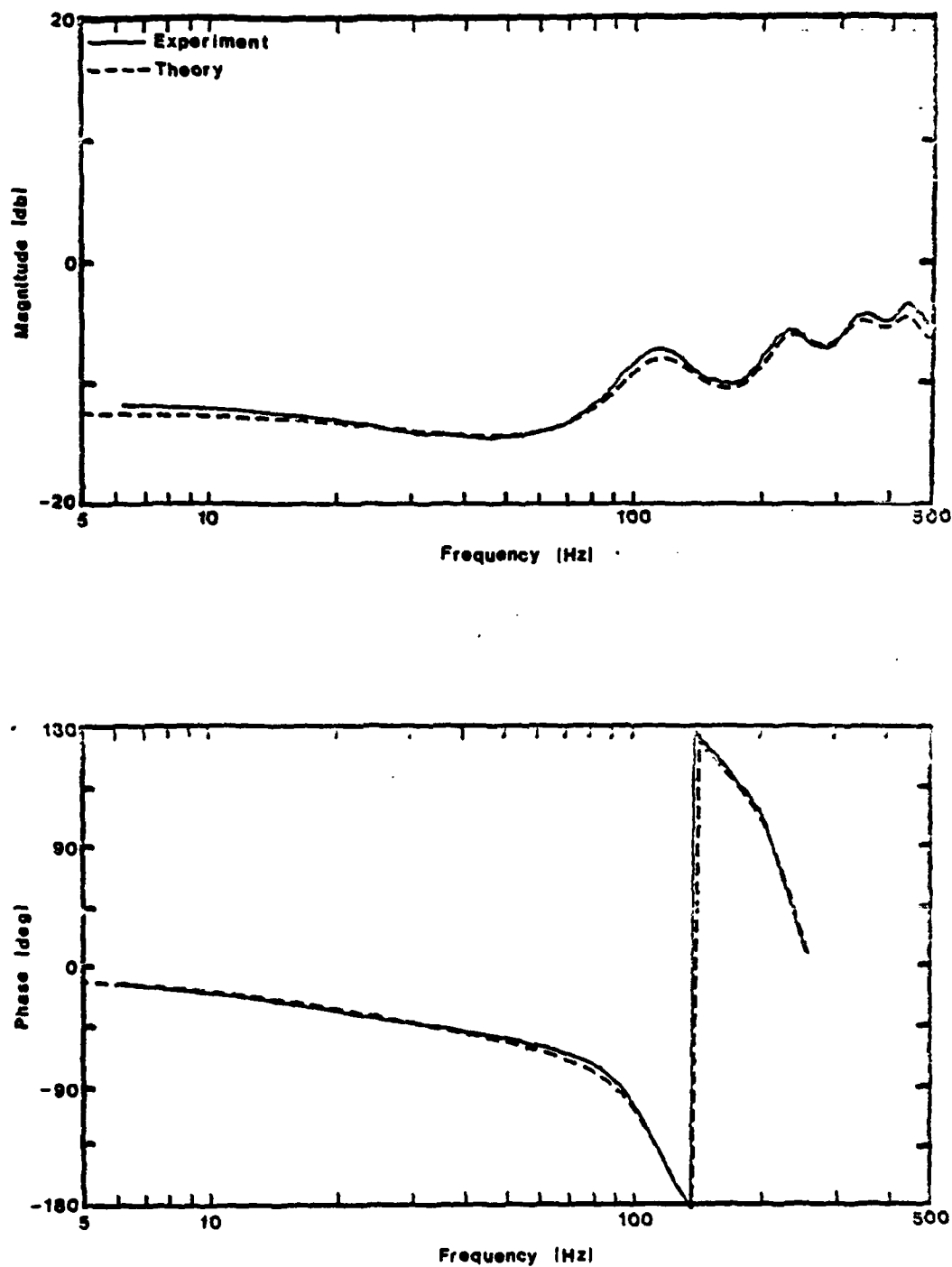


Fig 14. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Load: Resistor #4,  $l = 50\text{mm}$ ,  
 $d = .716\text{mm}$ )

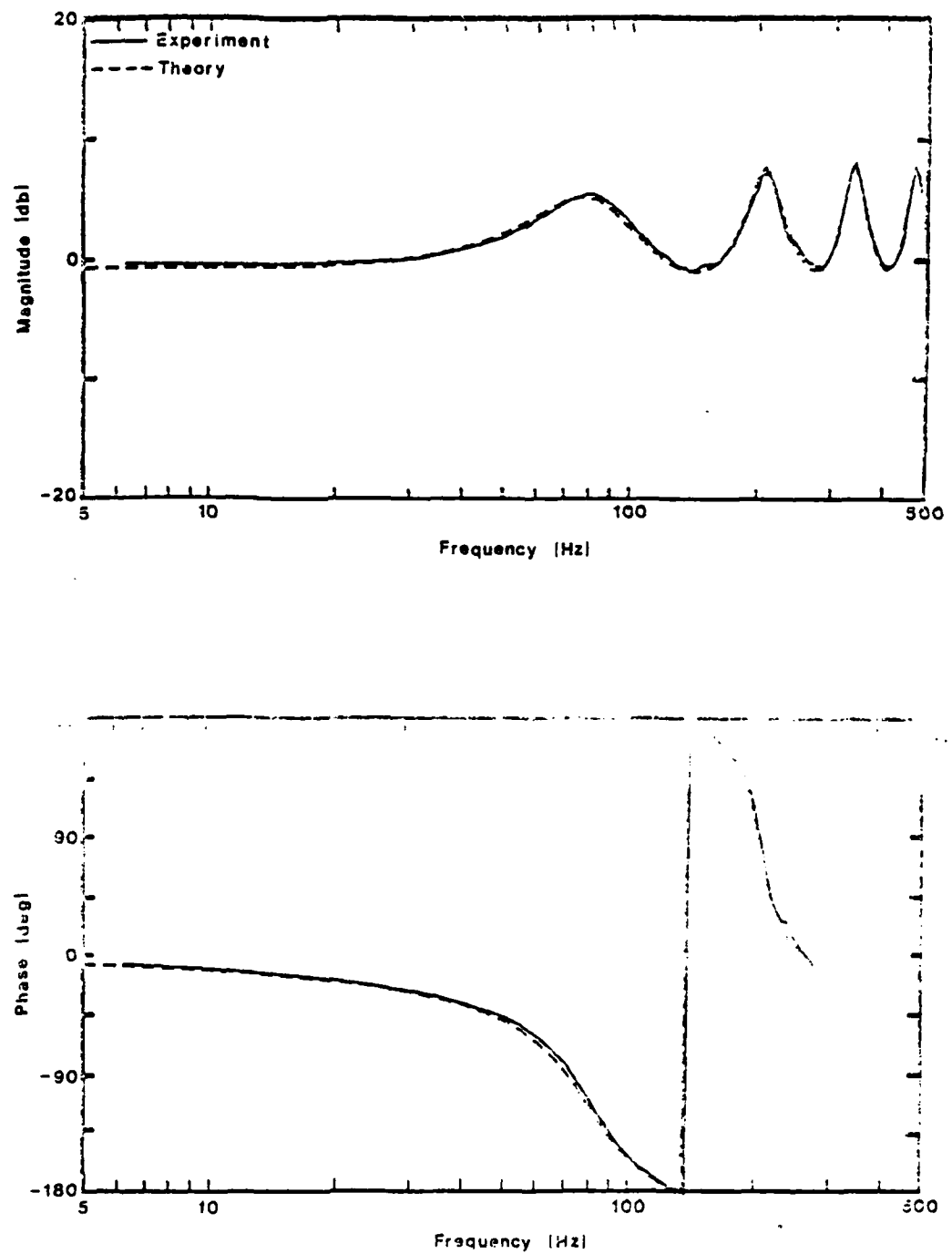


Fig 15. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Load: Resistor #4,  $l = 50\text{mm}$ ,  
 $d = .716\text{mm}$ )

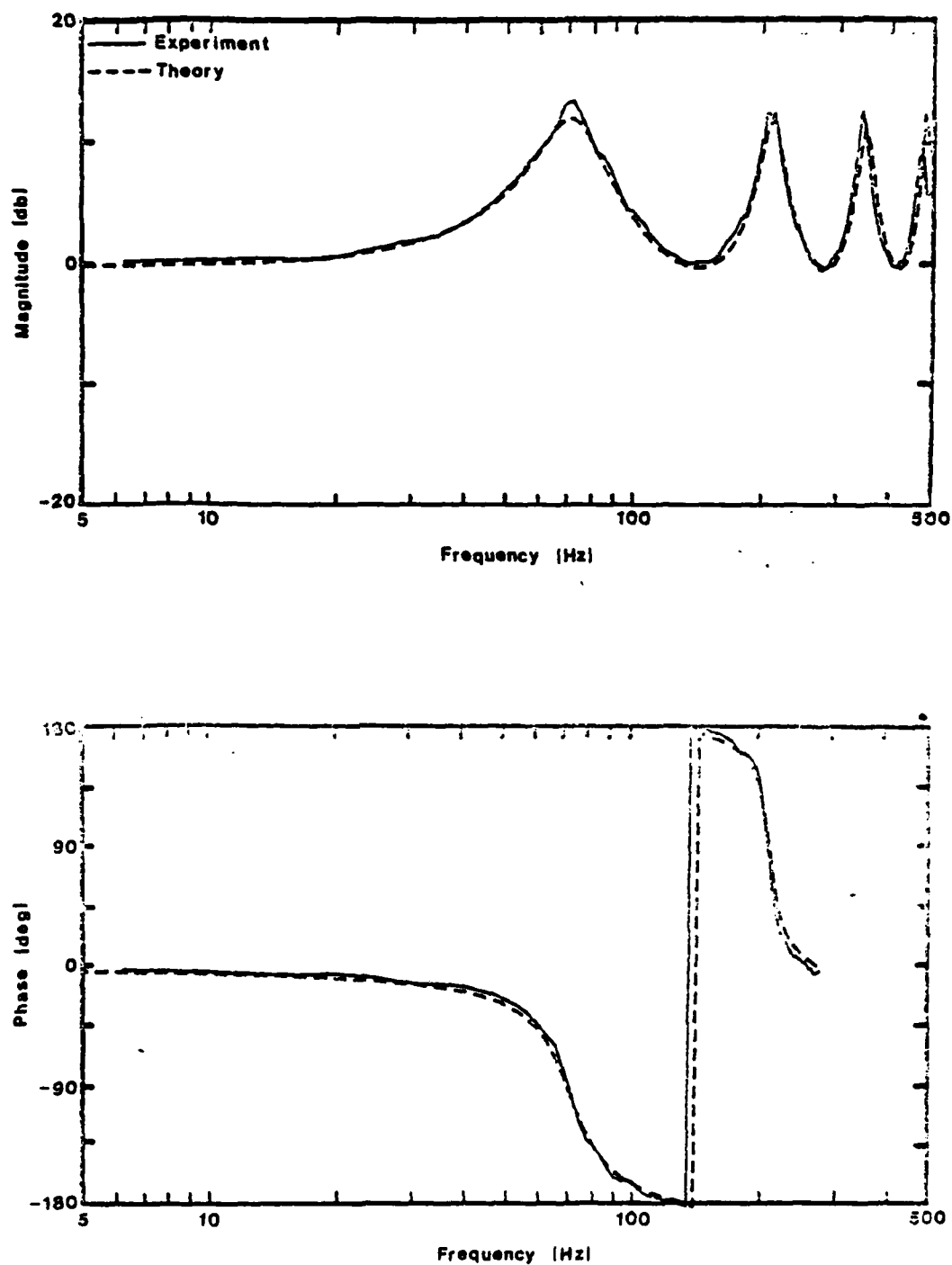


Fig 16. Frequency Response of Hydraulic Transmission Line  
( $\lambda = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Load: Resistor #4,  $\lambda = 50\text{mm}$ ,  
 $d = .716\text{mm}$ )

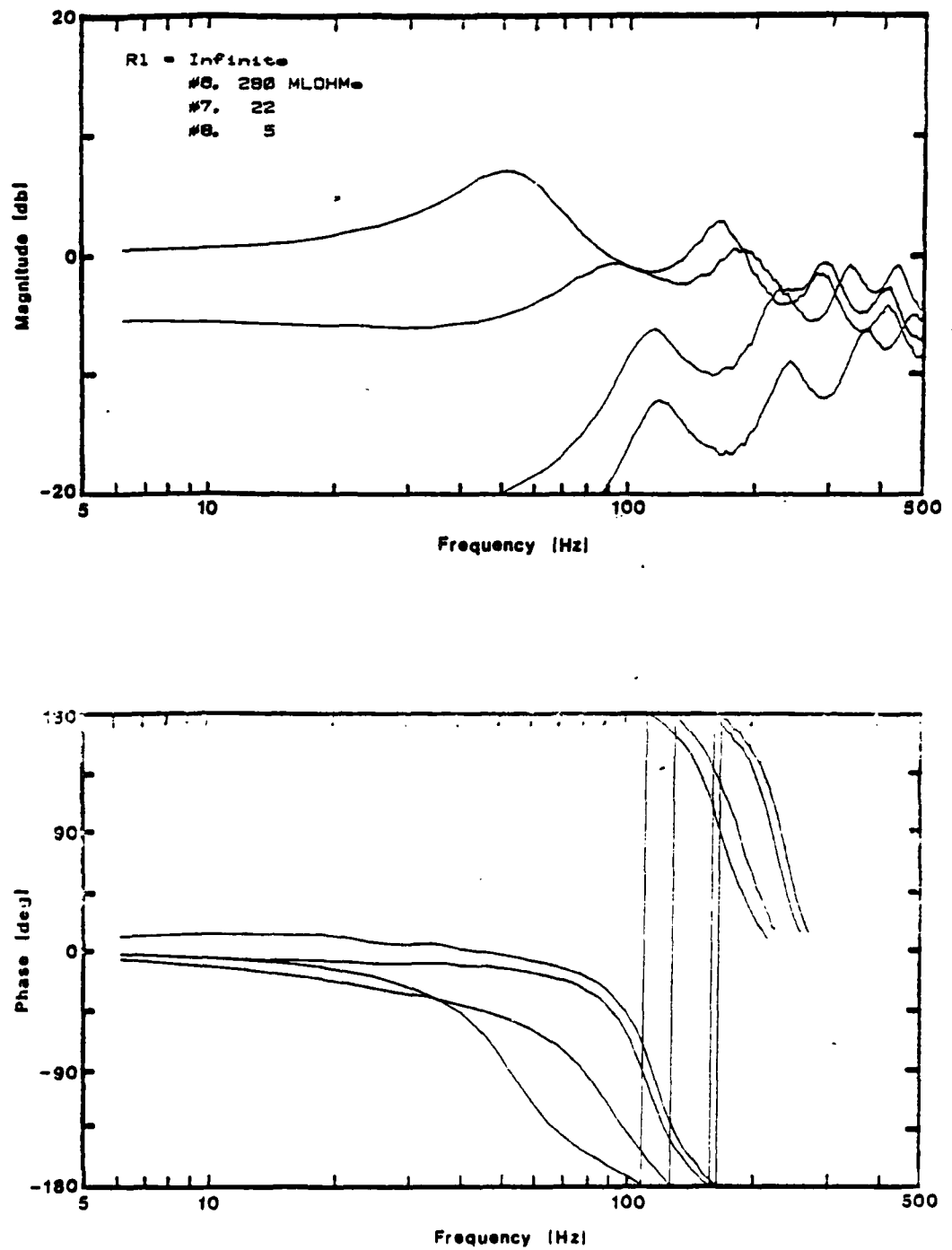


Fig 17. Frequency Response of Hydraulic Transmission Line  
(Experimental,  $\lambda = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ )

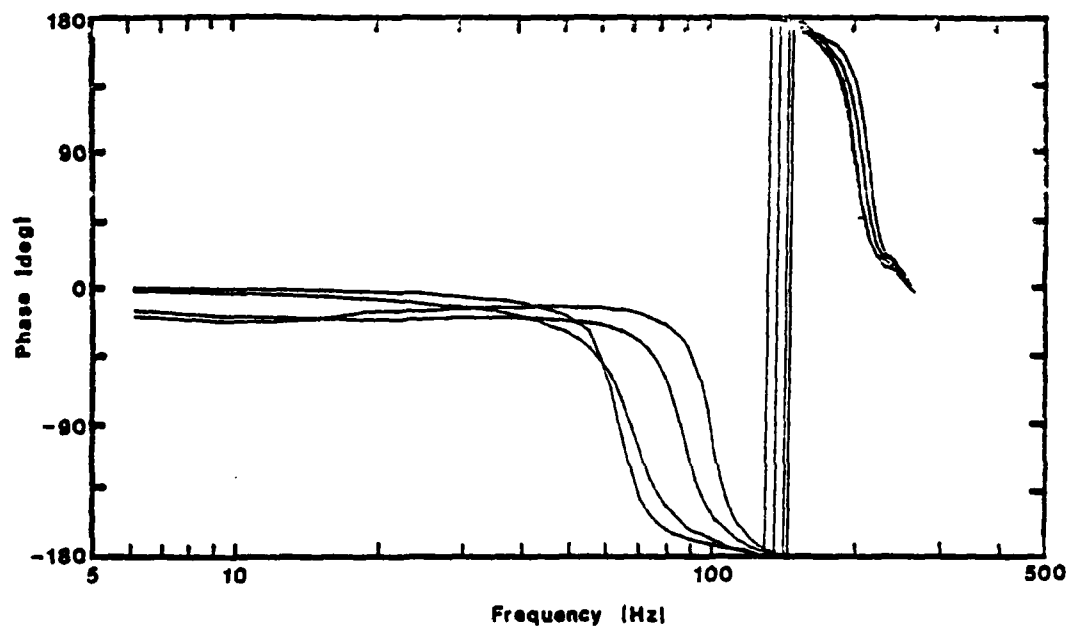
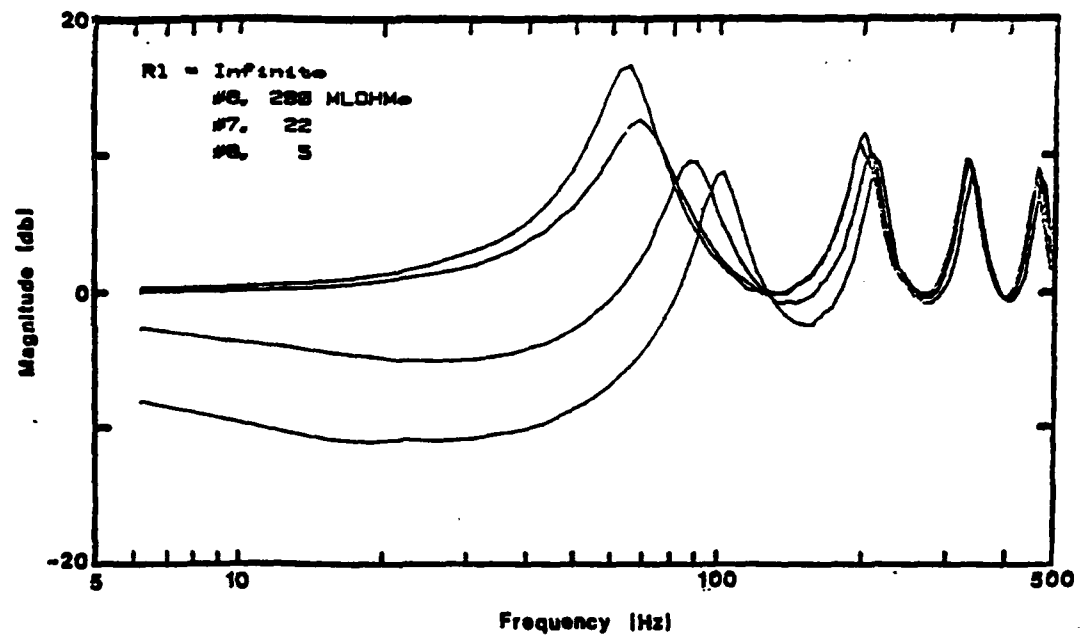


Fig 18. Frequency Response of Hydraulic Transmission Line  
(Experimental,  $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ )

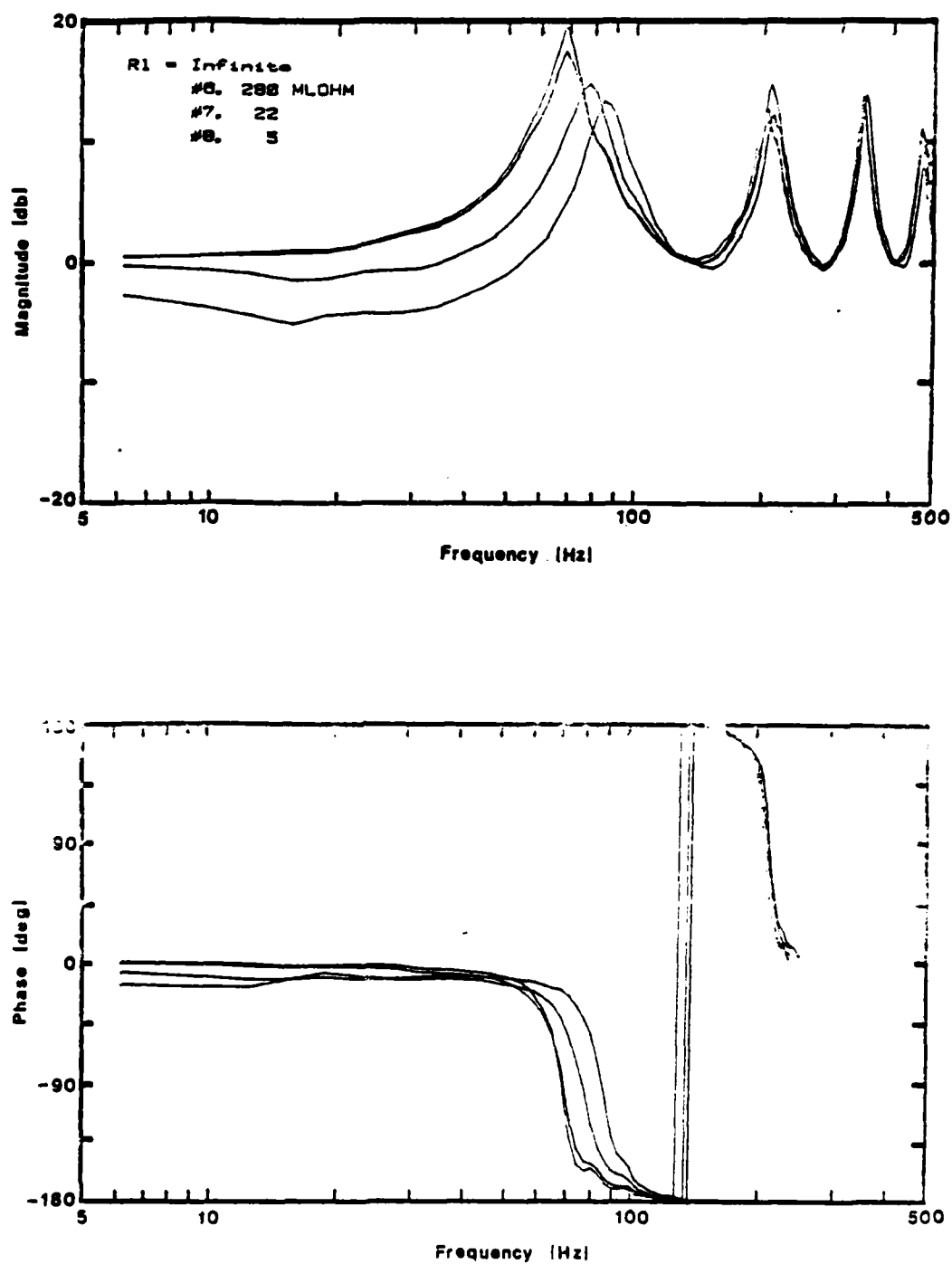


Fig 19. Frequency Response of Hydraulic Transmission Line  
(Experimental,  $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ )

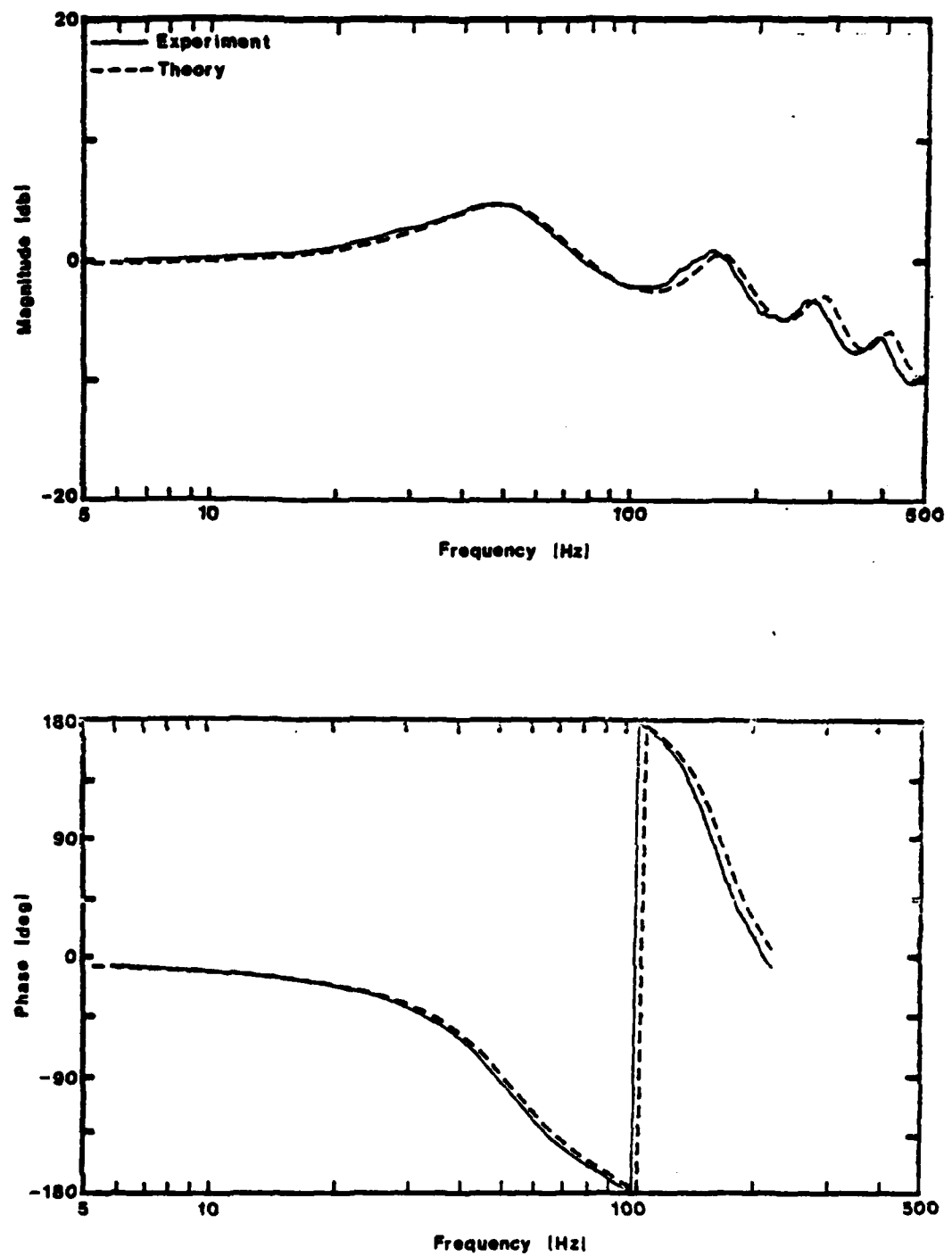


Fig 20. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Source: Resistor #1,  $R_S = 100\text{ M}\Omega$ )

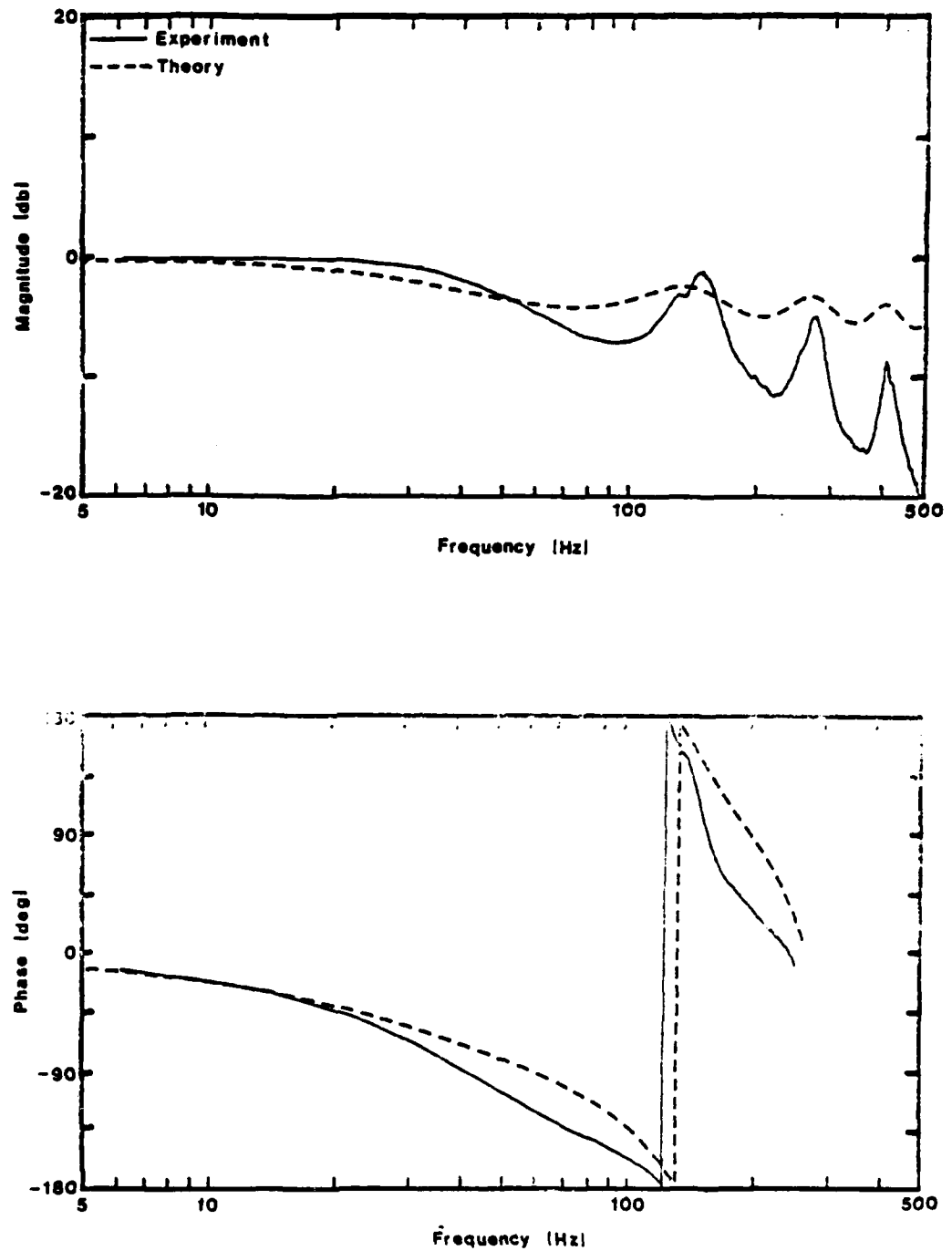


Fig 21. Frequency Response of Hydraulic Transmission Line  
 ( $\lambda = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Source: Resistor #1,  $R_s = 100\text{M}\Omega$ )

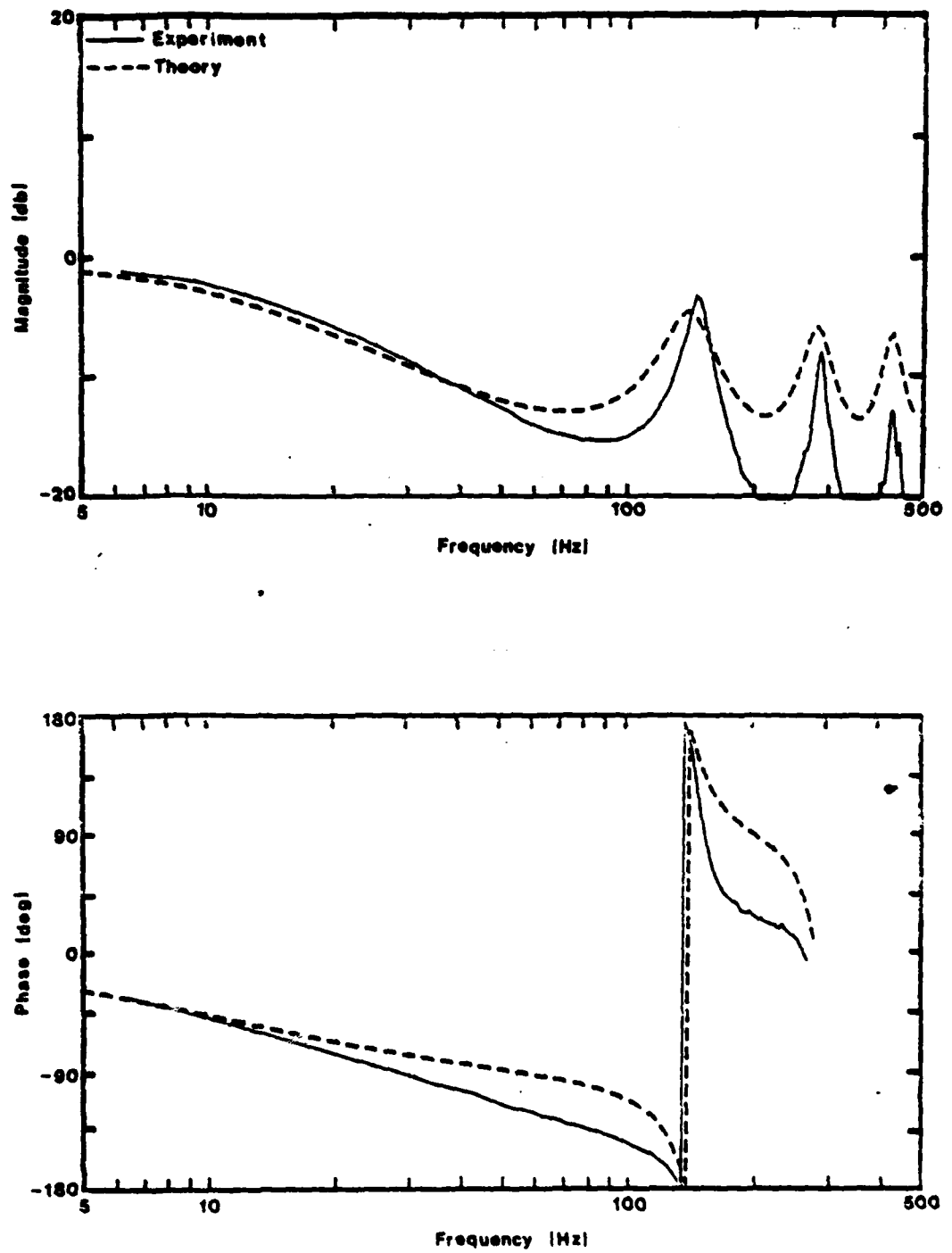


Fig 22. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Source: Resistor #1,  $R_S = 100\text{ M}\Omega$ )

Figures 23, 24, and 25 show the comparison of source resistance and inductance model with experiments.

The most accurate model is again the distributed-parameter cascaded-line model given below.

$$\frac{\delta P_b}{\delta P_s} = \frac{1}{\cosh \Gamma_s \cosh \Gamma + \frac{Z_{cs}}{Z_c} \sinh \Gamma_s \sinh \Gamma} \quad (33)$$

Figures 26, 27, and 28 show this model with the experimental results.

Figures 29, 30, and 31 show experimental responses at lines with different source impedances. Notice two effects: first, there is high frequency attenuation, as  $R_s$  increases, all resonant frequencies shift to the left, the first resonance eventually disappears, with the remaining resonances occur at even multiples of  $\pi/2$ ; second, there is a decrease in the  $-90^\circ$  bandwidth.

### 3.4 LOAD AND SOURCE IMPEDANCES

For ideal source resistance  $R_s$  and ideal load resistance  $R_L$ , the pressure transfer function is given below.

$$\frac{\delta P_b}{\delta P_s} = \frac{1}{(1 + \frac{R_s}{R_L}) \cosh \Gamma + (\frac{R_s}{Z_c} + \frac{Z_c}{R_L}) \sinh \Gamma} \quad (34)$$

Figures 32, 33, and 34 show the ideal  $R_s$  and  $R_L$  model along with experimental results. Again, considerable deviation between theory and experiment can be noticed.

By considering the inductive effects of the source and the load, the following transfer function can be obtained.

$$\frac{\delta P_b}{\delta P_s} = \frac{1}{(1 + \frac{R_s + L_s D}{R_L + L_L D}) \cosh \Gamma + (\frac{R_s + L_s D}{Z_c}) \sinh \Gamma} \quad (35)$$

Figures 35, 36, and 37 show the  $R_s L_s$  and  $R_L L_L$  model along with the respective experimental results. The correlation between theory and experiment is improved; however, some deviation still exists.

Figures 38, 39, and 40 show the more accurate cascaded line model along with experiments. Good agreement can be noticed. Lines with both source impedance and load impedance have combined effects and since there are many characterizing parameters, generalized responses are not presented in this report; however, refer to Appendix A for the data and the corresponding theory.

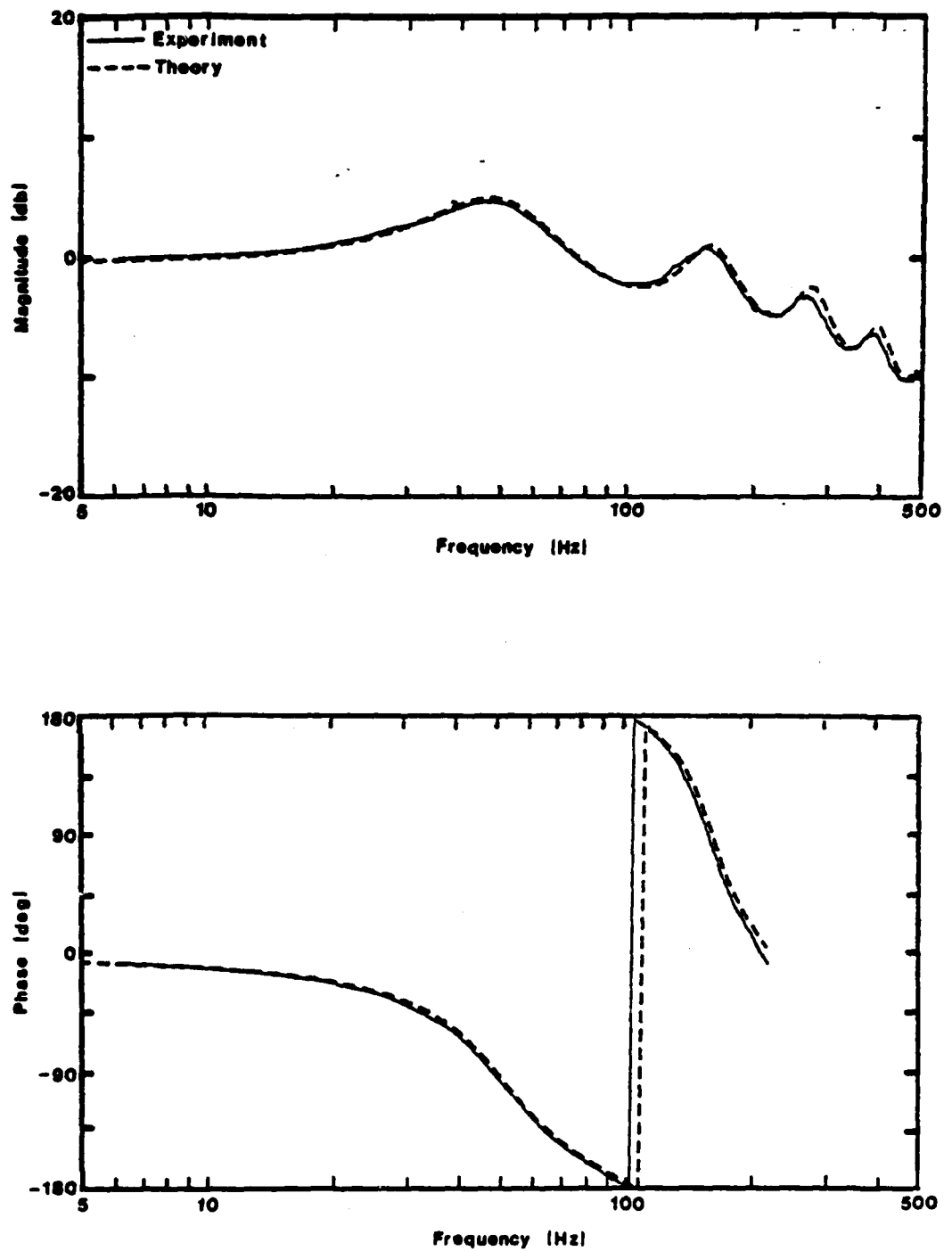


Fig 23. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Source: Resistor #1,  
 $R_S = 100\text{ M}\Omega$ ,  $L_S = .112\text{ }\mu\text{Henry}$ )

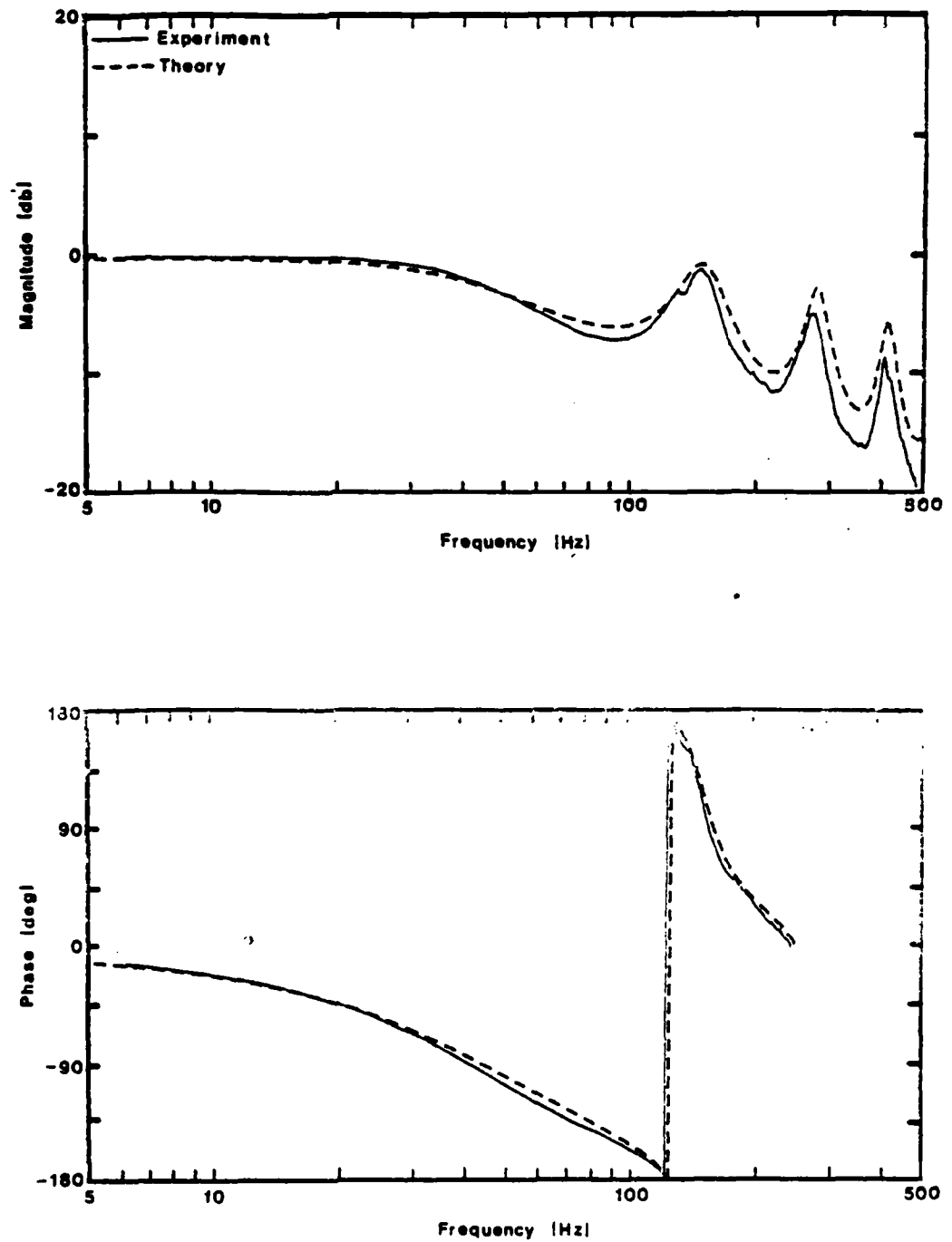


Fig 24. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Source: Resistor #1,  
 $R_S = 100\text{ M}\Omega$ ,  $L_S = .112\text{ Henry}$ )

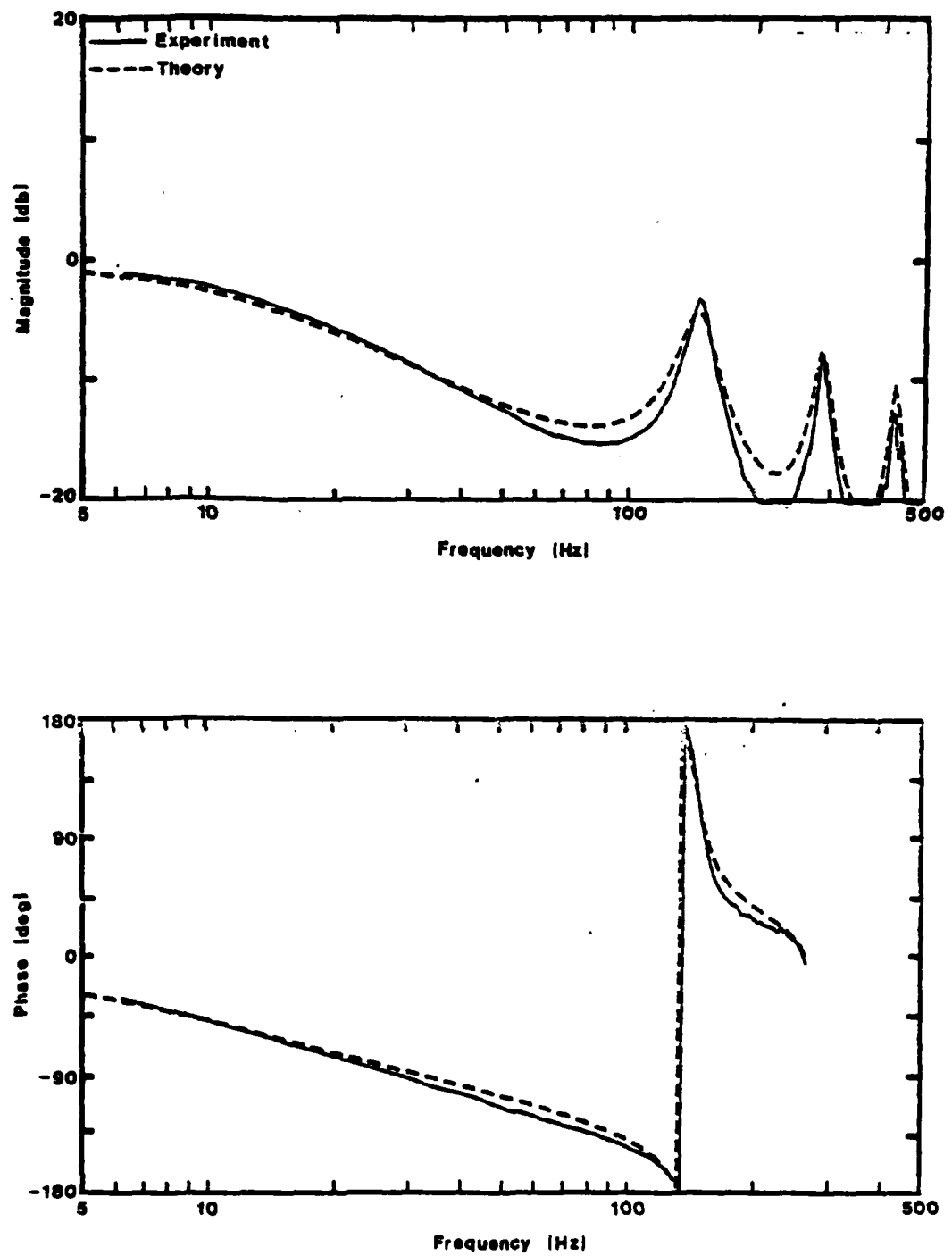


Fig 25. Frequency Response of Hydraulic Transmission Line  
 ( $\lambda = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Source: Resistor #1,  
 $R_S = 100\text{ M}\Omega$ ,  $L_S = .112\text{ mH}$ )

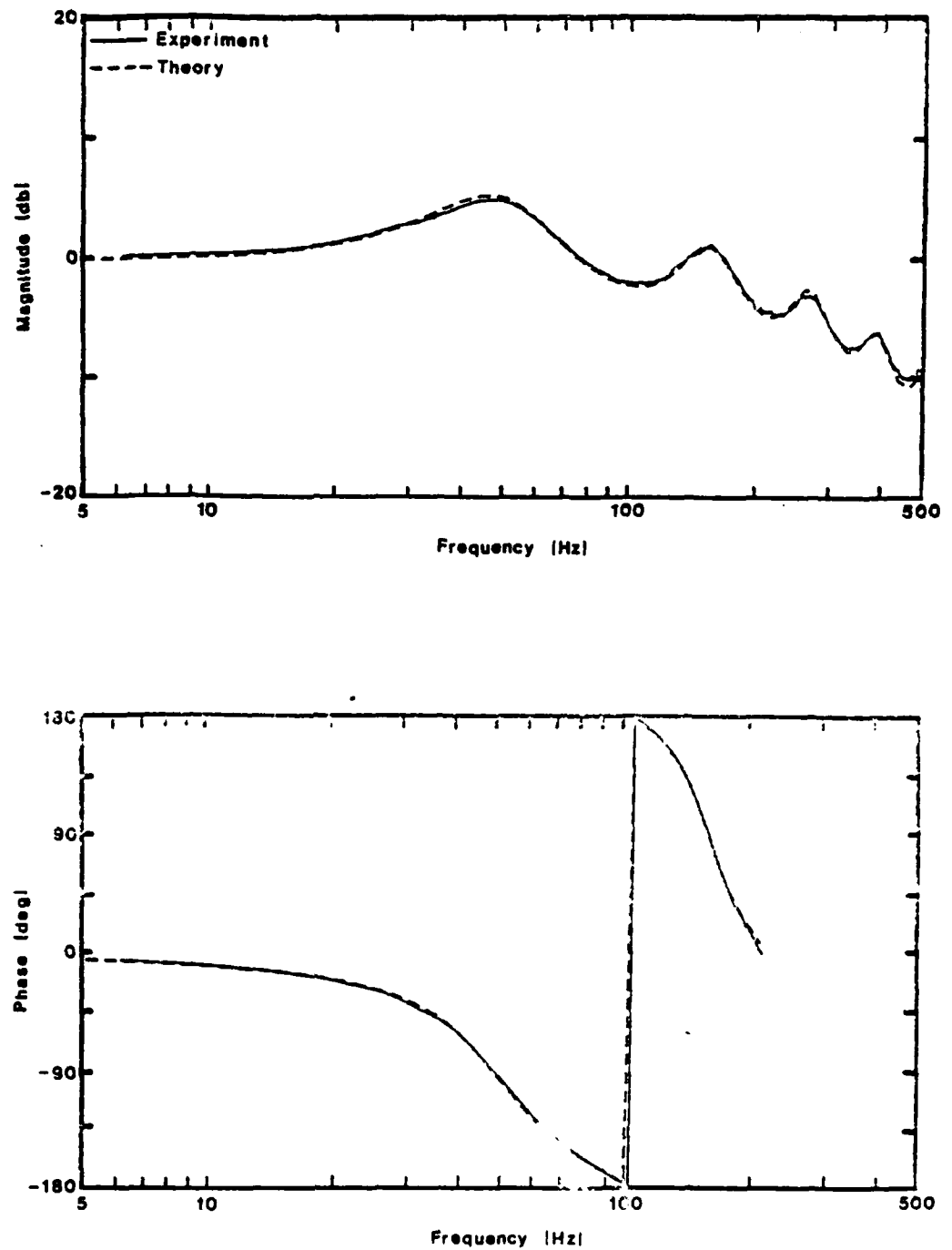


Fig 26. Frequency Response of Hydraulic Transmission Line  
( $\lambda = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Source: Resistor #1,  $\lambda = 53\text{mm}$ ,  
 $d = .716\text{mm}$ )

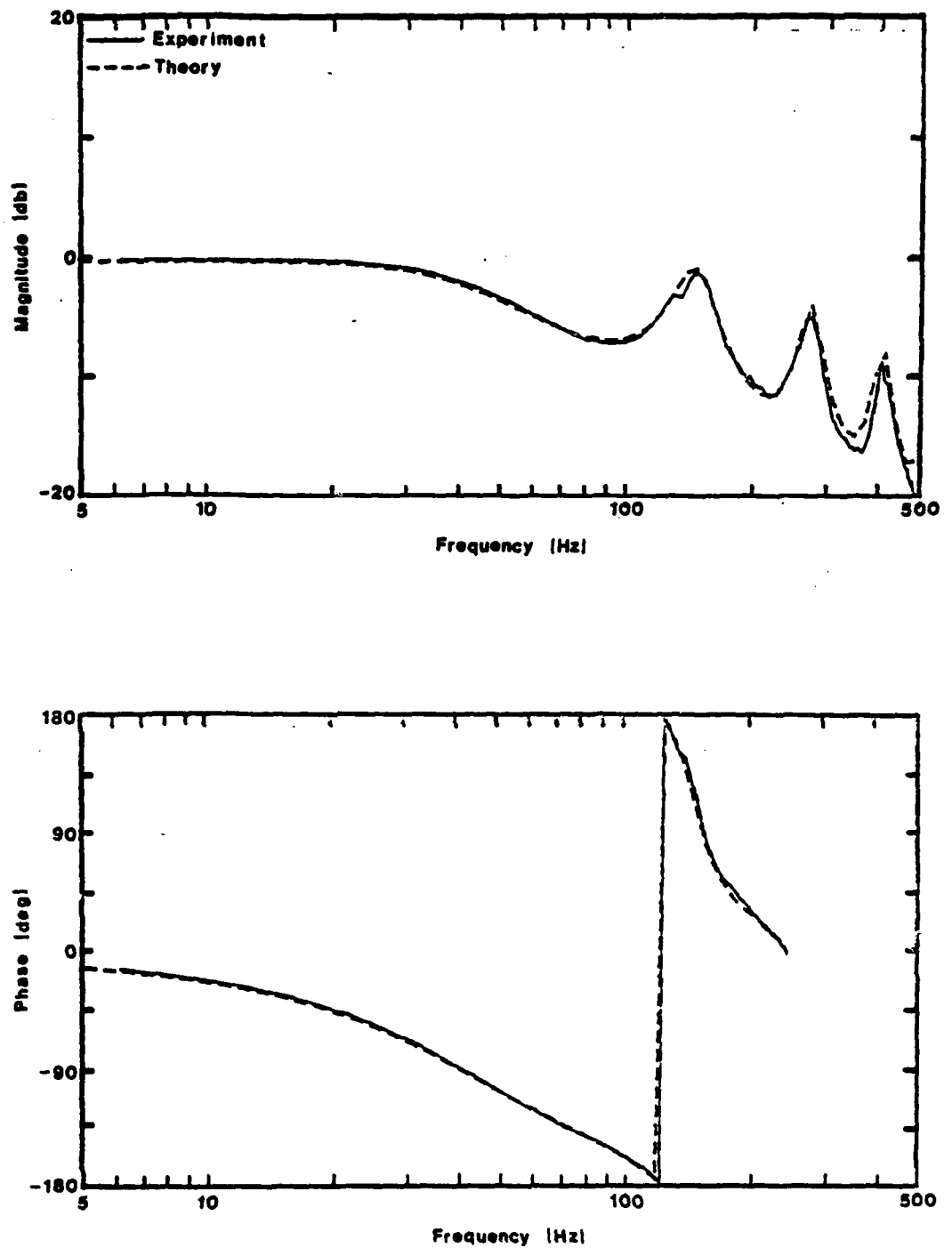


Fig 27. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Source: Resistor #1,  $l = 53\text{mm}$ ,  
 $d = .716\text{mm}$ )

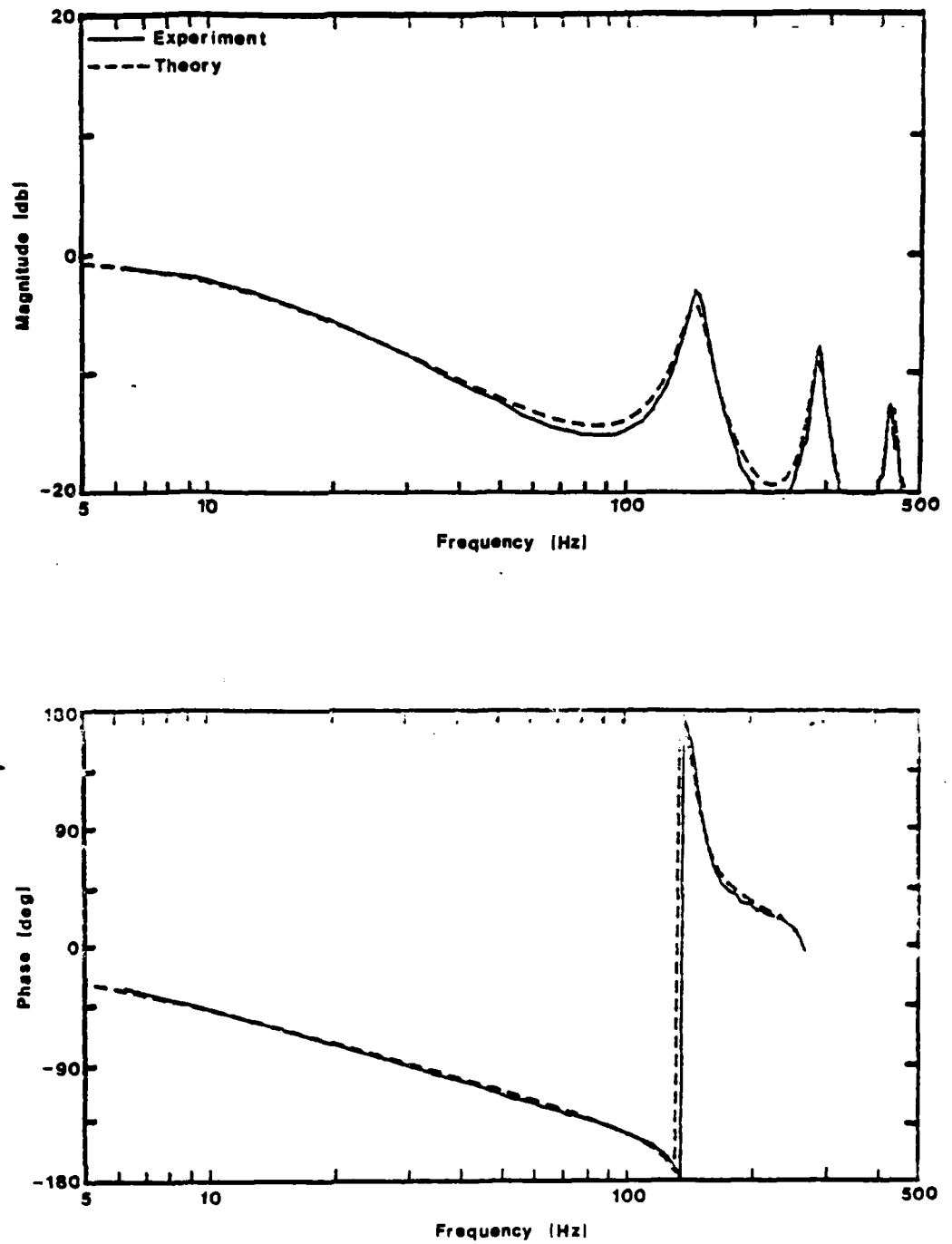


Fig 28. Frequency Response of Hydraulic Transmission Line  
( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Source: Resistor #1,  $l = 53\text{mm}$ ,  
 $d = .716\text{mm}$ )

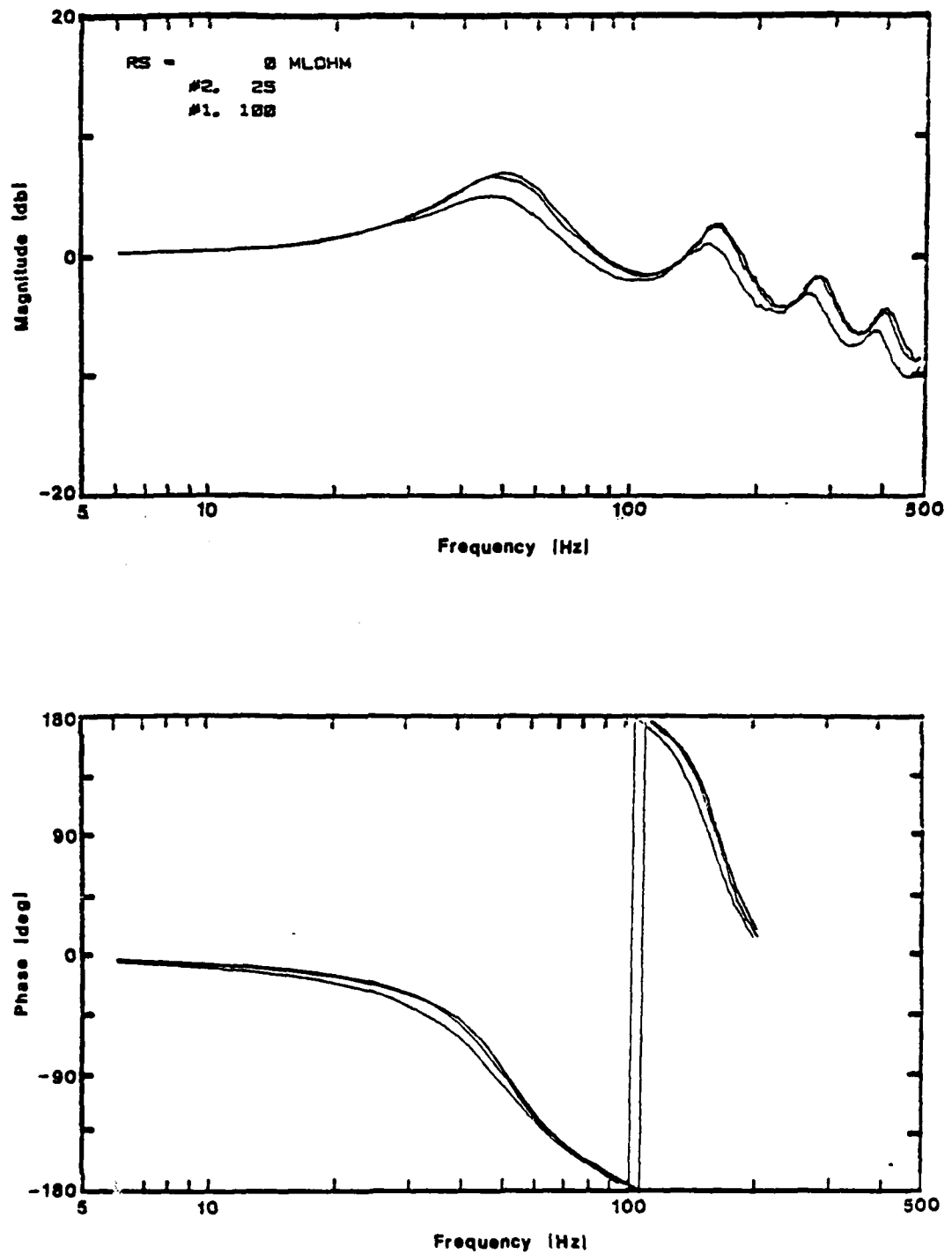


Fig 29. Frequency Response of Hydraulic Transmission Line  
(Experimental,  $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ )

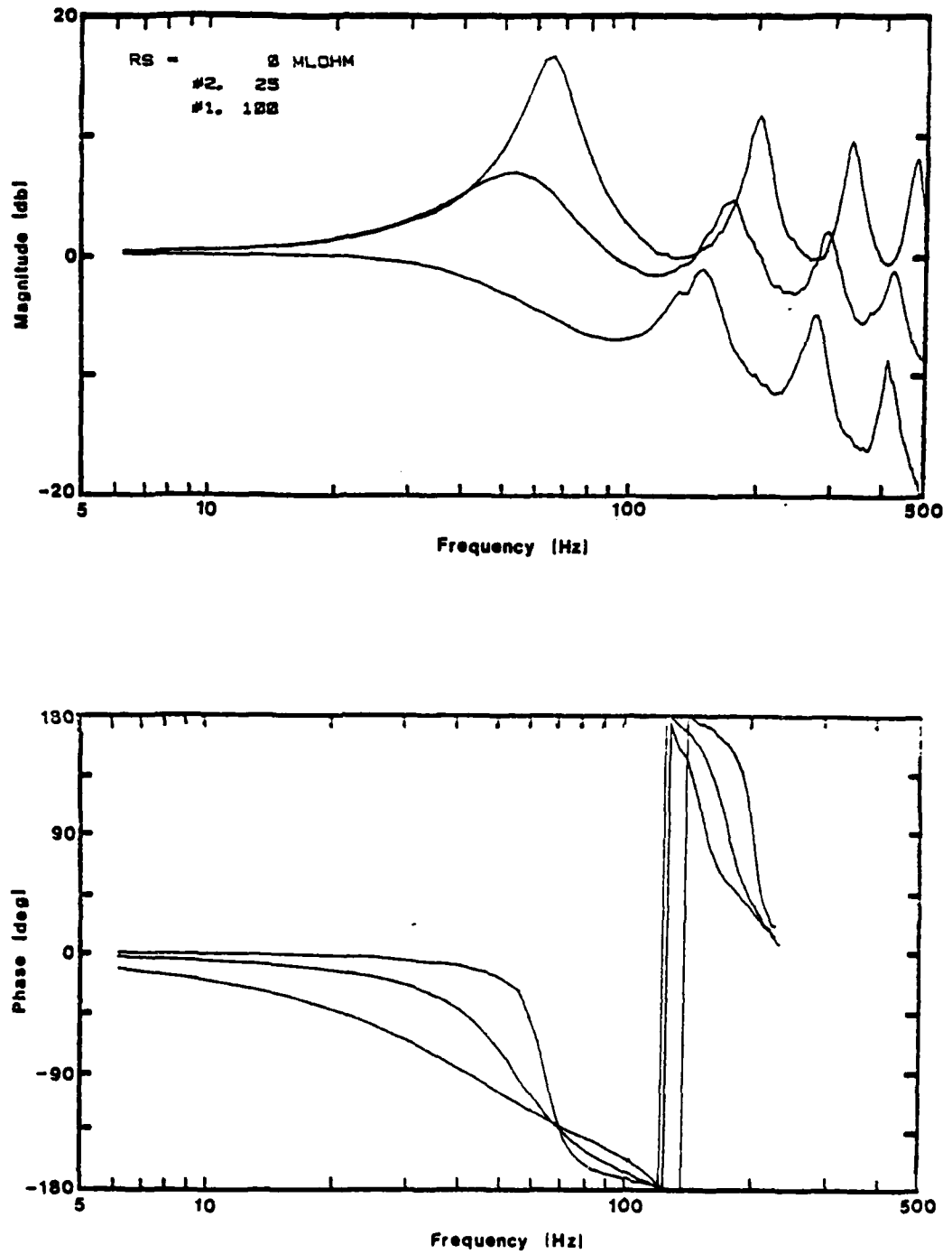


Fig 30. Frequency Response of Hydraulic Transmission Line  
(Experimental,  $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ )

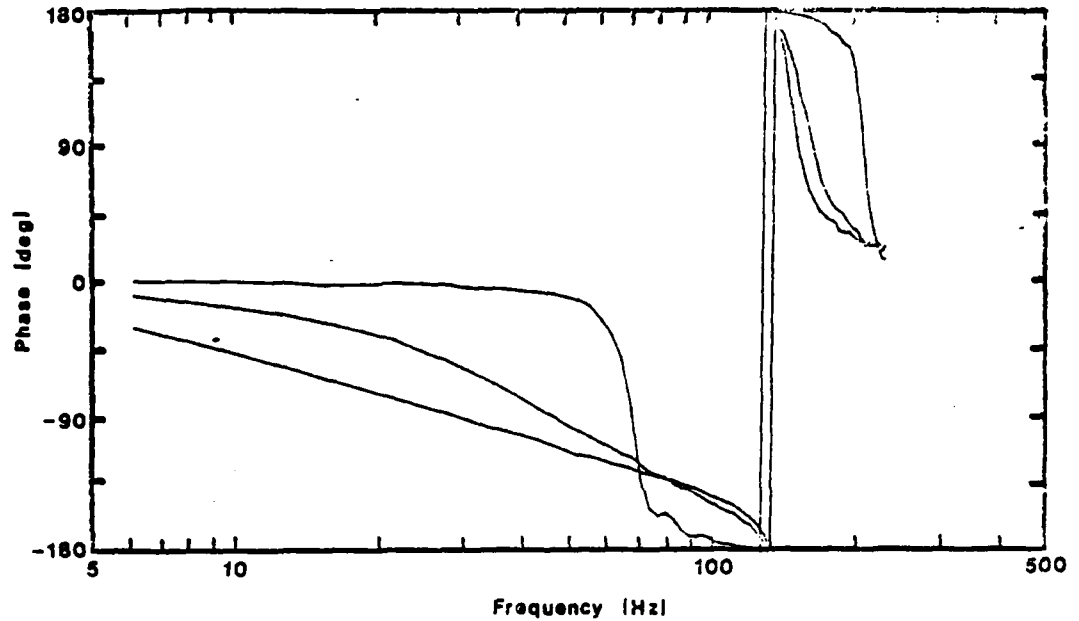
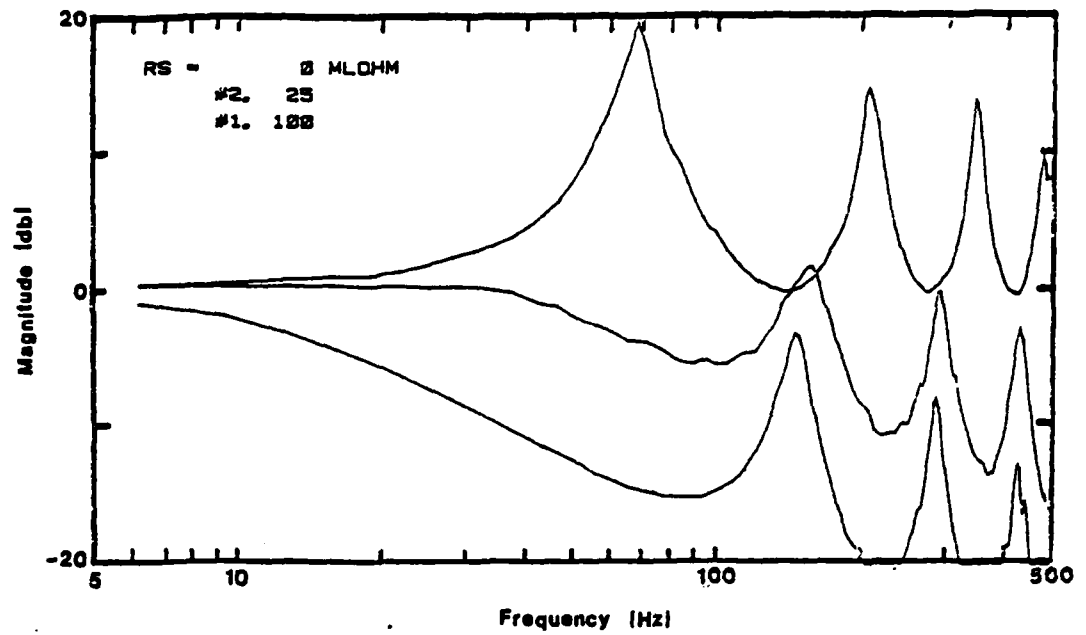


Fig 31. Frequency Response of Hydraulic Transmission Line  
(Experimental,  $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ )

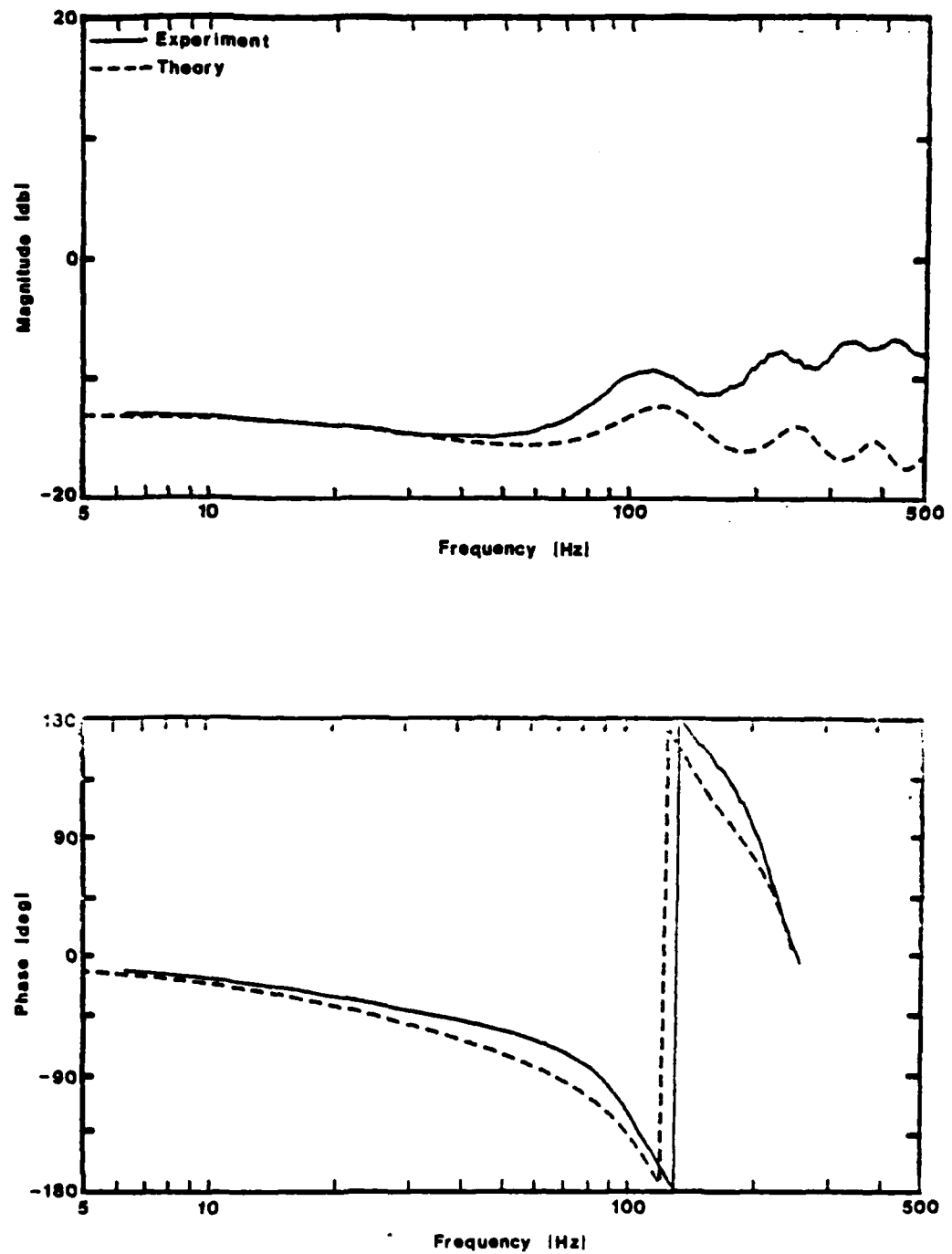


Fig 32. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Source: Resistor #1,  $R_S = 100\text{ M}\Omega$ ; Load: Resistor #4,  $R_L = 92\text{ M}\Omega$ )

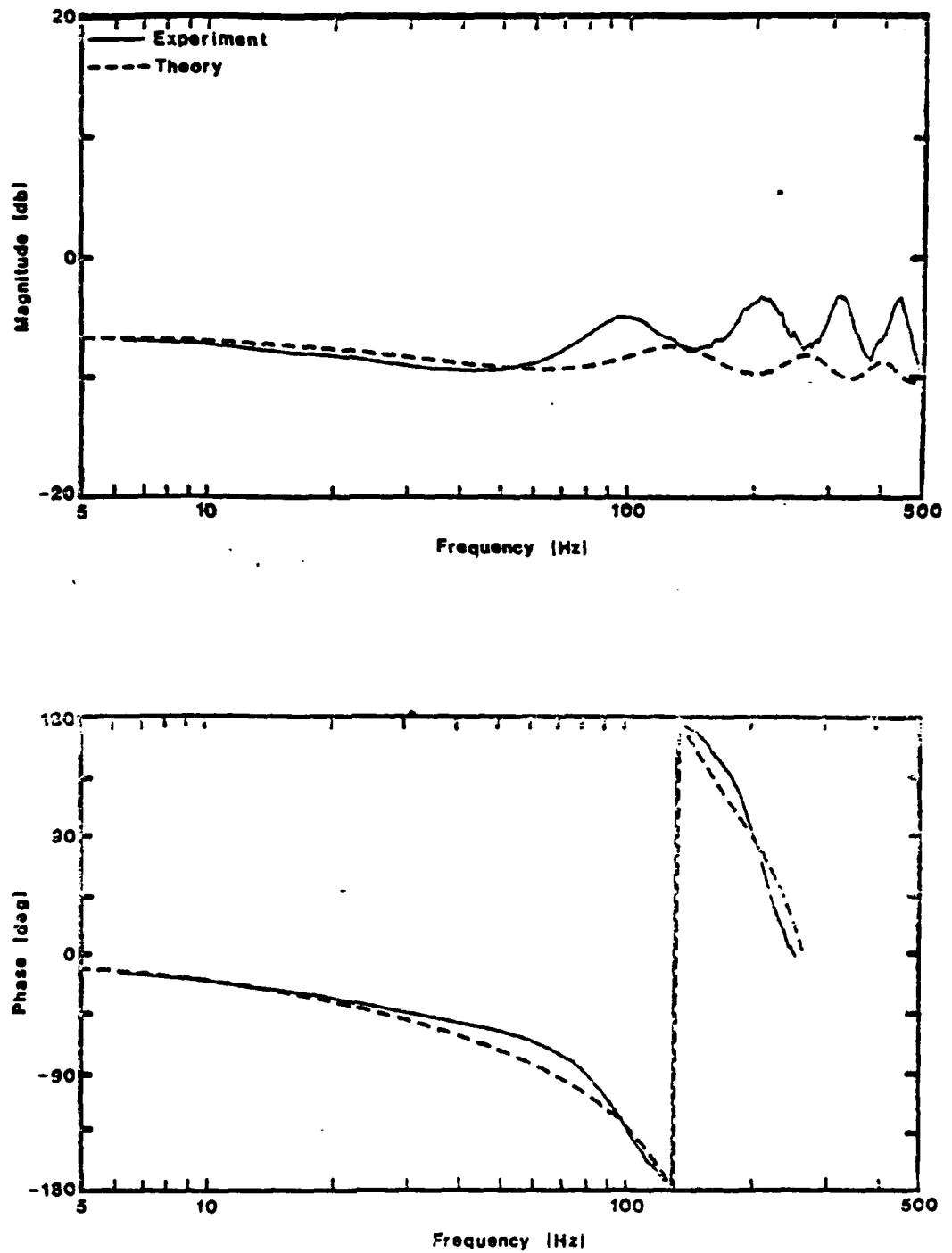


Fig 33. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Source: Resistor #2,  
 $R_S = 25\text{ M}\Omega$ ; Load: Resistor #5,  $R_L = 23\text{ M}\Omega$ )

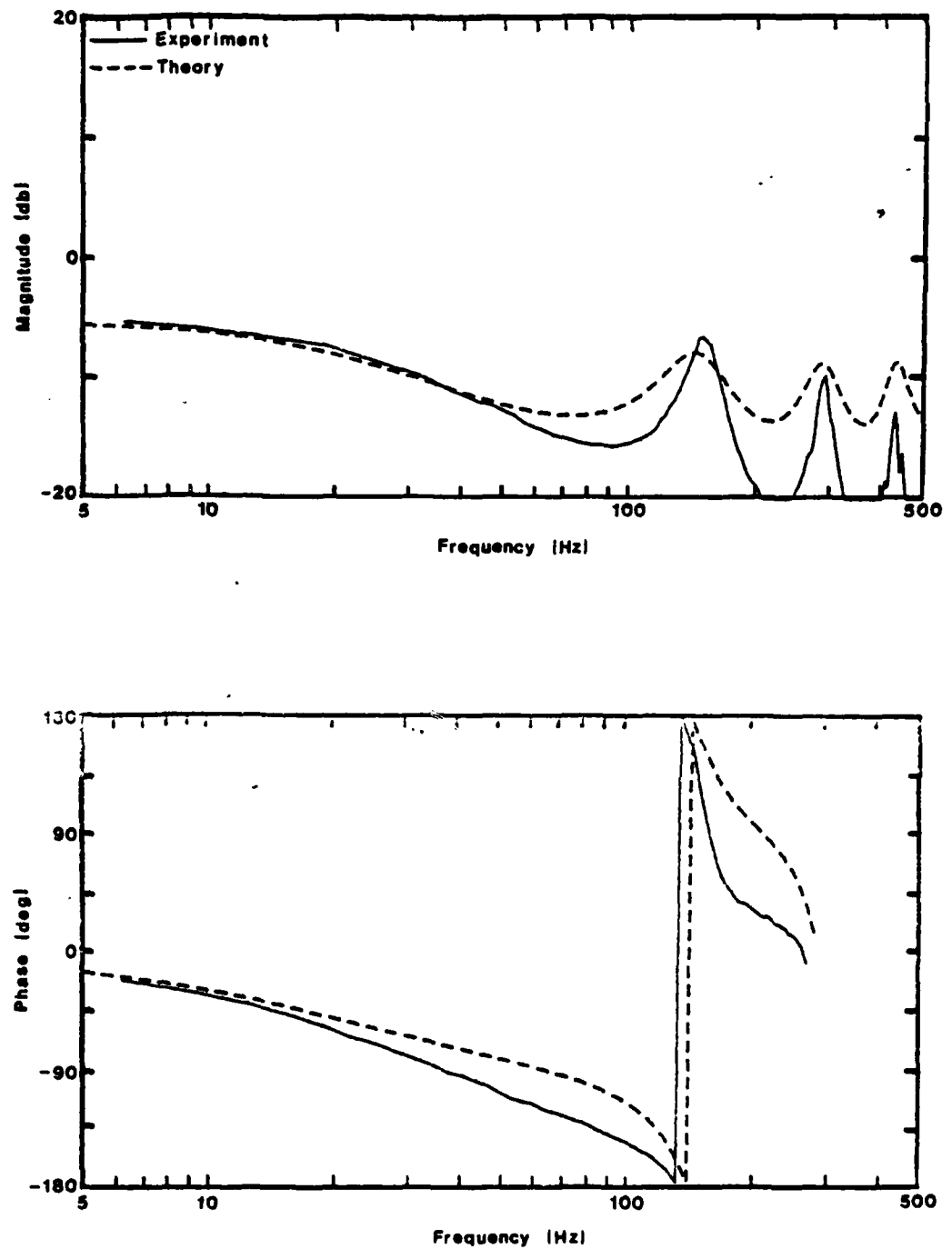


Fig 34. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Source: Resistor #1,  
 $R_S = 100\text{ M}\Omega$ ; Load : Resistor #4,  $R_L = 92\text{ M}\Omega$ )

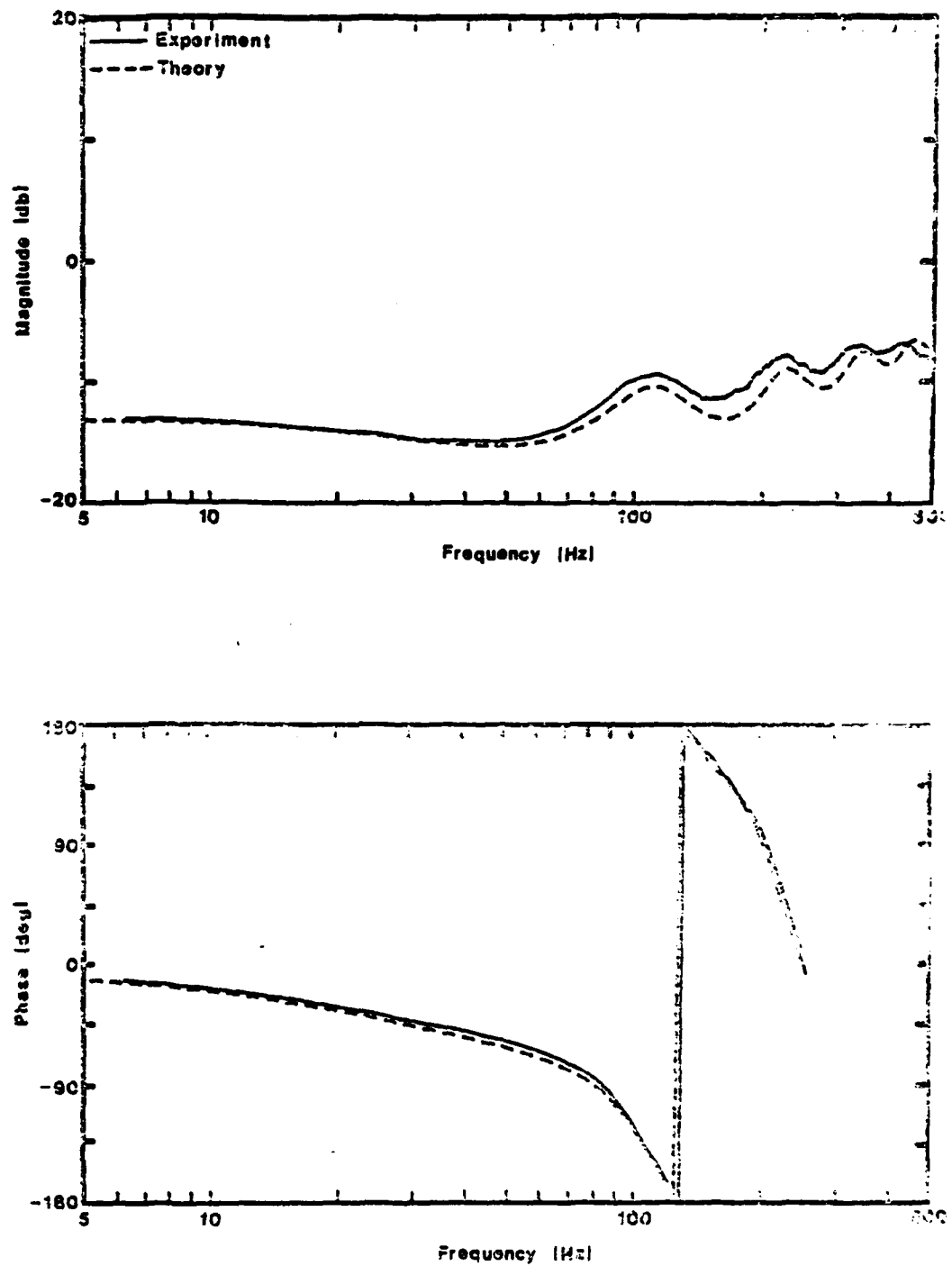


Fig 35. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Source: Resistor #1,  
 $R_S = 100\text{ M}\Omega$ ,  $L_S = .112\text{ MHenry}$ ; Load: Resistor #4,  
 $R_L = 92\text{ M}\Omega$ ,  $L_L = .105\text{ MHenry}$ )

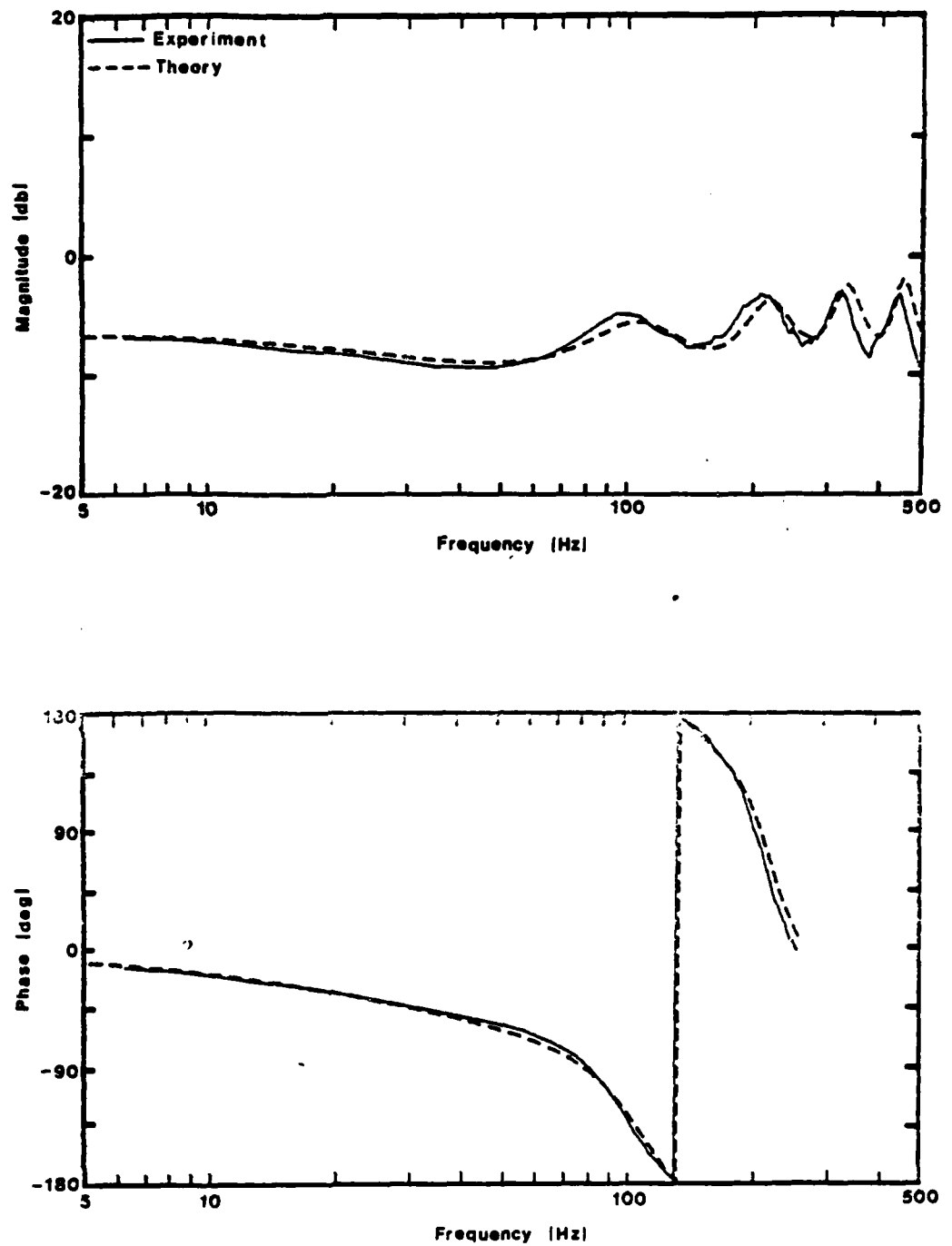


Fig 36. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Source: Resistor #2,  
 $R = 25\text{ M}\Omega$ ,  $L_S = .028\text{ mH}$ ; Load: Resistor #5,  
 $R_L^S = 23\text{ M}\Omega$ ,  $L_L^S = .0275\text{ mH}$ )

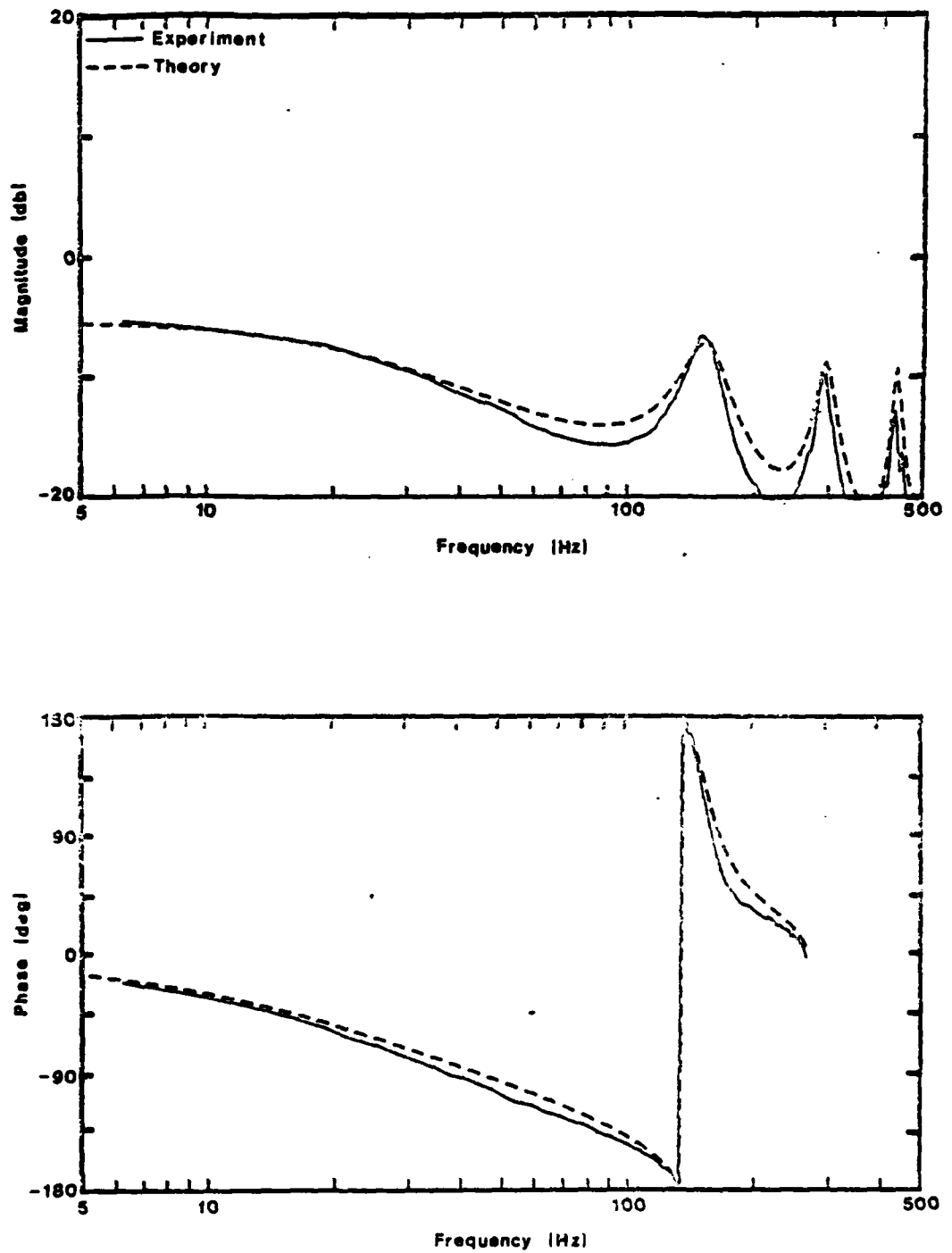


Fig 37. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Source: Resistor #1,  
 $R_S = 100\text{ M}\Omega$ ,  $L_S = .112\text{ MHenry}$ ; Load: Resistor #4,  
 $R_L = 92\text{ M}\Omega$ ,  $L_L = .105\text{ MHenry}$ )

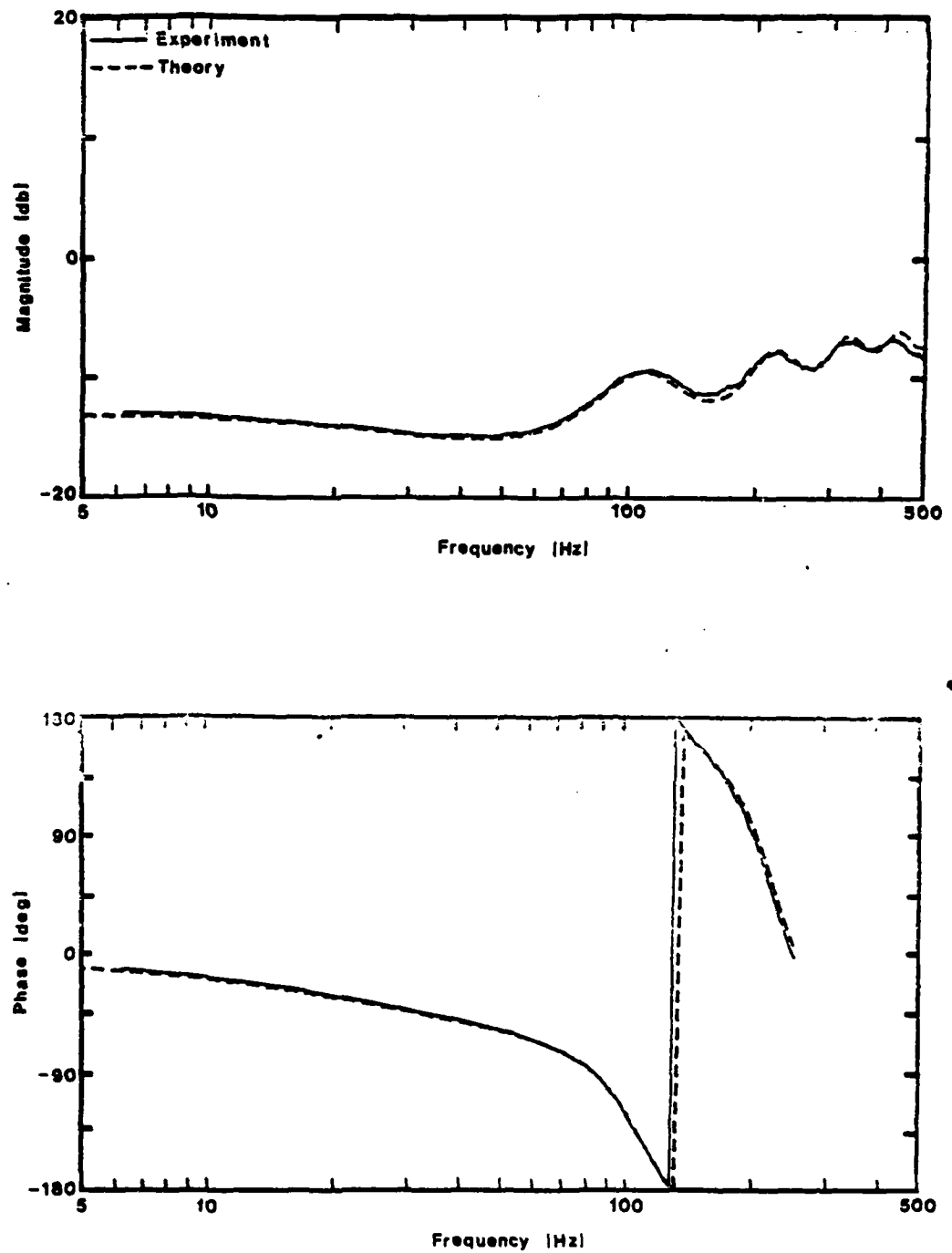


Fig 38. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 1.7\text{mm}$ ; Source: Resistor #1,  $l = 53\text{mm}$ ,  
 $d = .716\text{mm}$ ; Load: Resistor #4,  $l = 50\text{mm}$ ,  $d = .716\text{mm}$ )

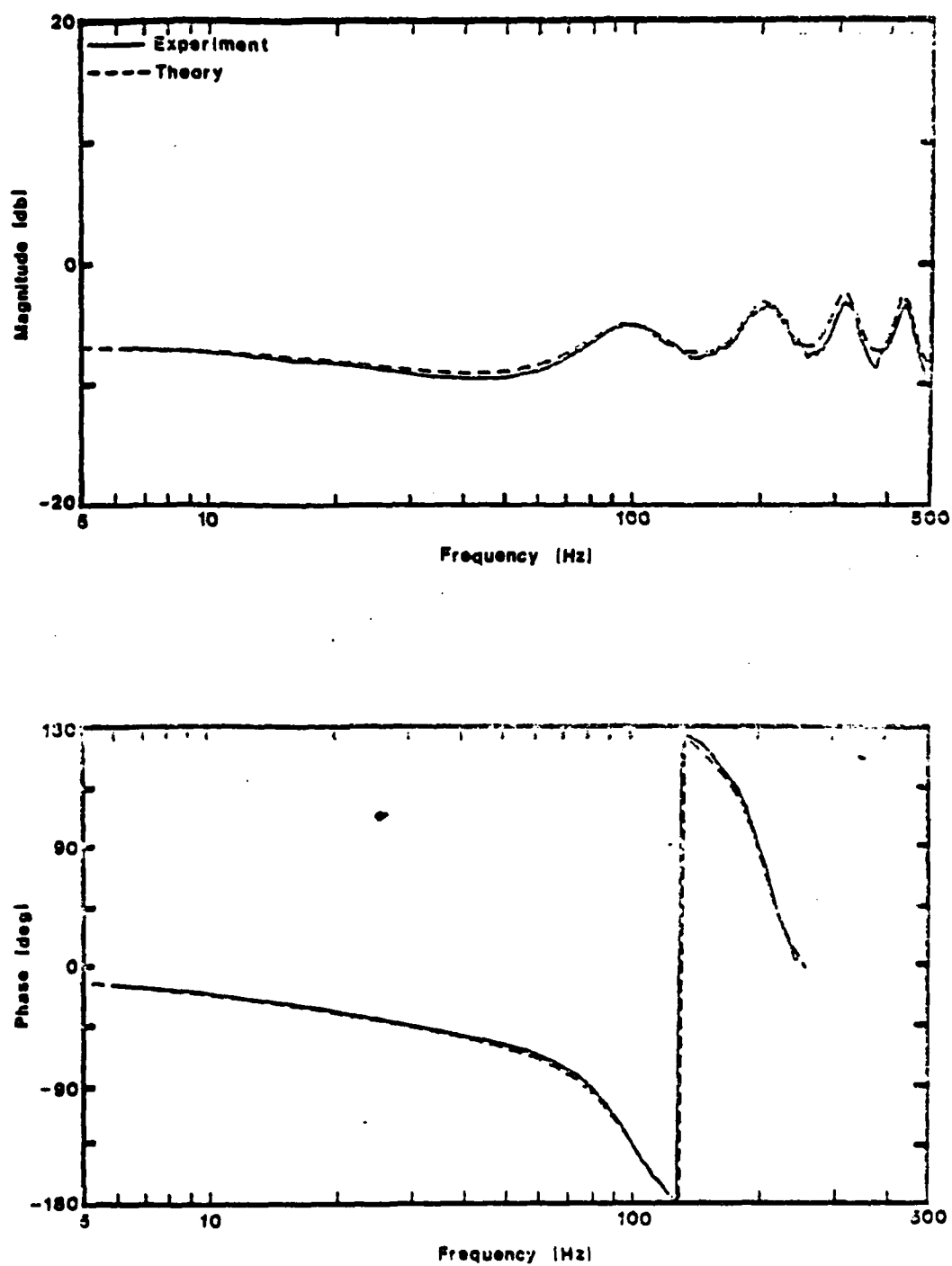


Fig 39. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 4.8\text{mm}$ ; Source: Resistor #2,  $l = 53\text{mm}$ ,  
 $d = .716\text{mm}$ , 4 tubes; Load: Resistor #5,  $l = 52\text{mm}$ ,  
 $d = .716\text{mm}$ , 4 tubes)

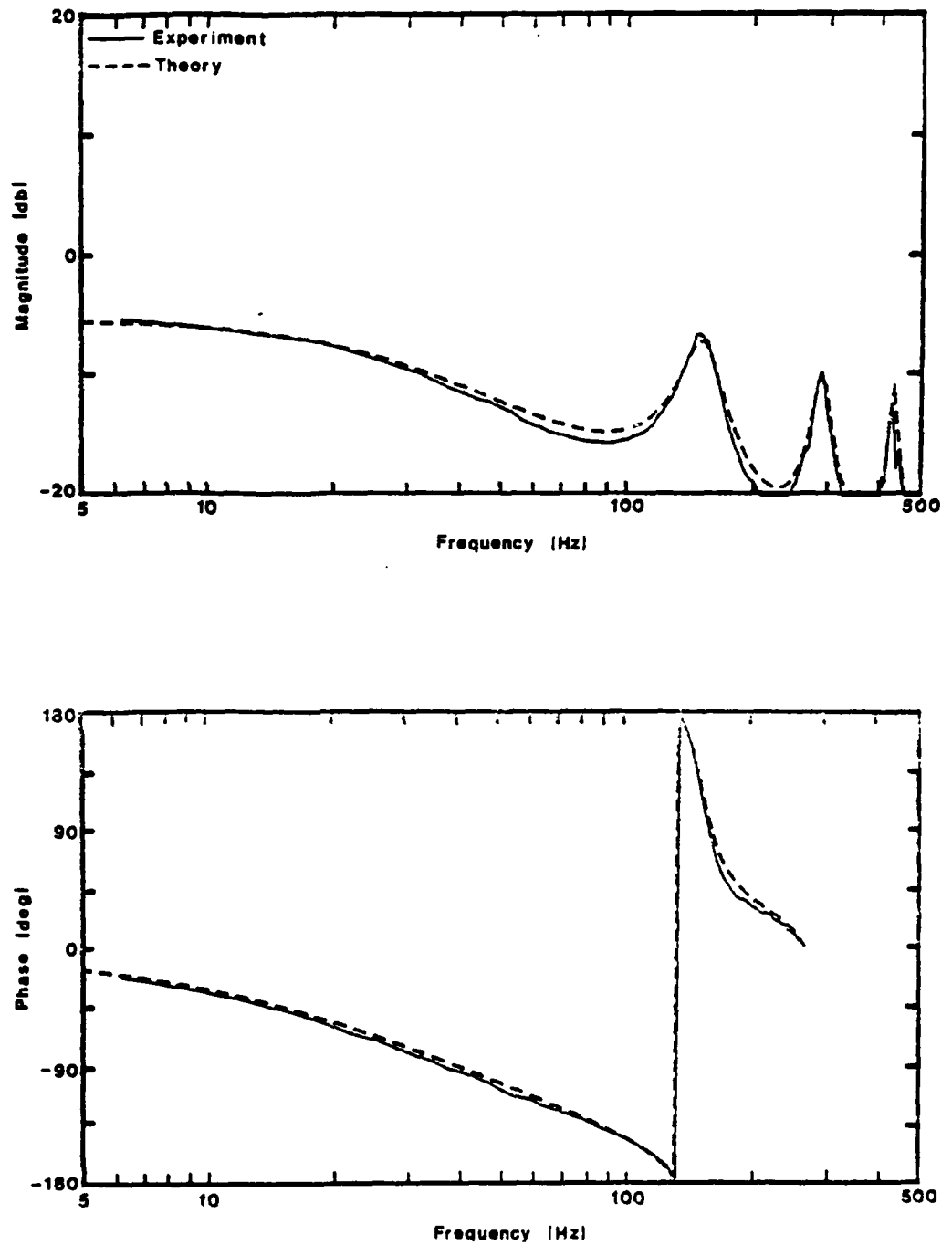


Fig 40. Frequency Response of Hydraulic Transmission Line  
 ( $l = 4.8\text{m}$ ,  $d = 7.6\text{mm}$ ; Source: Resistor #1,  $l = 53\text{mm}$ ,  
 $d = .716\text{mm}$ ; Load: Resistor #4,  $l = 50\text{mm}$ ,  $d = .716\text{mm}$ )



#### 4. SUMMARY AND CONCLUSIONS

Presented in this report are the frequency responses of many combinations of hydraulic transmission lines with source and load impedances typical of fluidic control circuits. Theoretical models of varying degrees of complexity are compared to the experimental data. The agreement is within one dB and a few degrees.

Capillary tubes were used as source or load impedances connected to hydraulic signal transmission lines. It was discovered that a simple resistance model for a capillary tube was not adequate at high frequency where inductance of the capillary becomes significant. A lumped-parameter model can be used; however, the best model for the capillary is a distributed-parameter model connected in series with the line model.

The inductive effect was unexpected since the capillary was so short in comparison to the line length that the separation in characteristic frequencies would be large. If this were true, we would expect no dynamic effects until the excitation frequency approached the capillary line characteristic frequency which was above the frequency range of the test. The unexpected variation in response is due to the variation of the load or source capillary with frequency. The characteristic impedance of the capillary changes at the viscous frequency,  $\omega_v$ , and thus changes the response.

Thus, when a long and a short line are connected together, the short line will alter the dynamics of the long line at frequencies around the corner frequency of the short line. This frequency of the short line is the smaller of either the characteristic frequency or the viscous frequency.

The excellent agreement between theory and experimental results presented here indicates that the theoretical models can be extended to other applications and configurations with confidence.

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1. Woods, R.L., "Fluidic Backup Flight Controls, A Feasibility Study", Navair Report #N00019-78-C-0460, Vought Corp., Dallas, June 1979.
2. Leonard, J.B., et. al., "Fluidic Flight Control Technology Evaluation: Problem Areas and Proposed Solutions", Navair Report #N00019-78-C-0459, Grumman Aerospace Corp., Dec. 1979.
3. Woods, R.L., "Breadboard Evaluation of a Single-Axis Fluidic Flight Control System", Navair Report #N00019-79-C-0433, Vought Corp., Dallas, May 1981.
4. Woods, R.L. and Hullender, D.A., "The Development of Components For a Fluidic Backup Flight Control System", Navair Report #N00019-79-C-0431, Univ. of Texas at Arlington, Feb 1981.
5. Brown, F.T., "The Transient Response of Fluid Lines", ASME J. of Basic Engr., Dec. 1962.

## Appendix A

EXPERIMENTAL RESPONSES

The purpose of this experimental study is to obtain the frequency response of hydraulic transmission lines with various adjoining source and load impedances and to compare the results to the corresponding theoretical response of the cascaded-lines model in order to verify the validity of the theory. Details of the procedure, equipment, and results are given below.

Procedure

The functional block diagram of the experimental apparatus is shown in Figure A1. A flapper-nozzle valve is driven by the random excitation signal from the digital signal analyzer to produce a random pressure signal at the upstream end of the transmission lines. The upstream and downstream pressures were continuously monitored with transducers that produce analog signals. A digital signal analyzer digitized the signals and computed their transfer function. The magnitude and phase of the transfer function is displayed graphically as a function of frequency (Bode plots).

The data were taken under continuous running conditions. Two mean operating pressures were used for each data to ensure that there was no entrained air or pressure-dependent nonlinearities in the lines. Temperature of the fluid was measured periodically during the experiments, and viscosity changes are taken into account when plotting theoretical

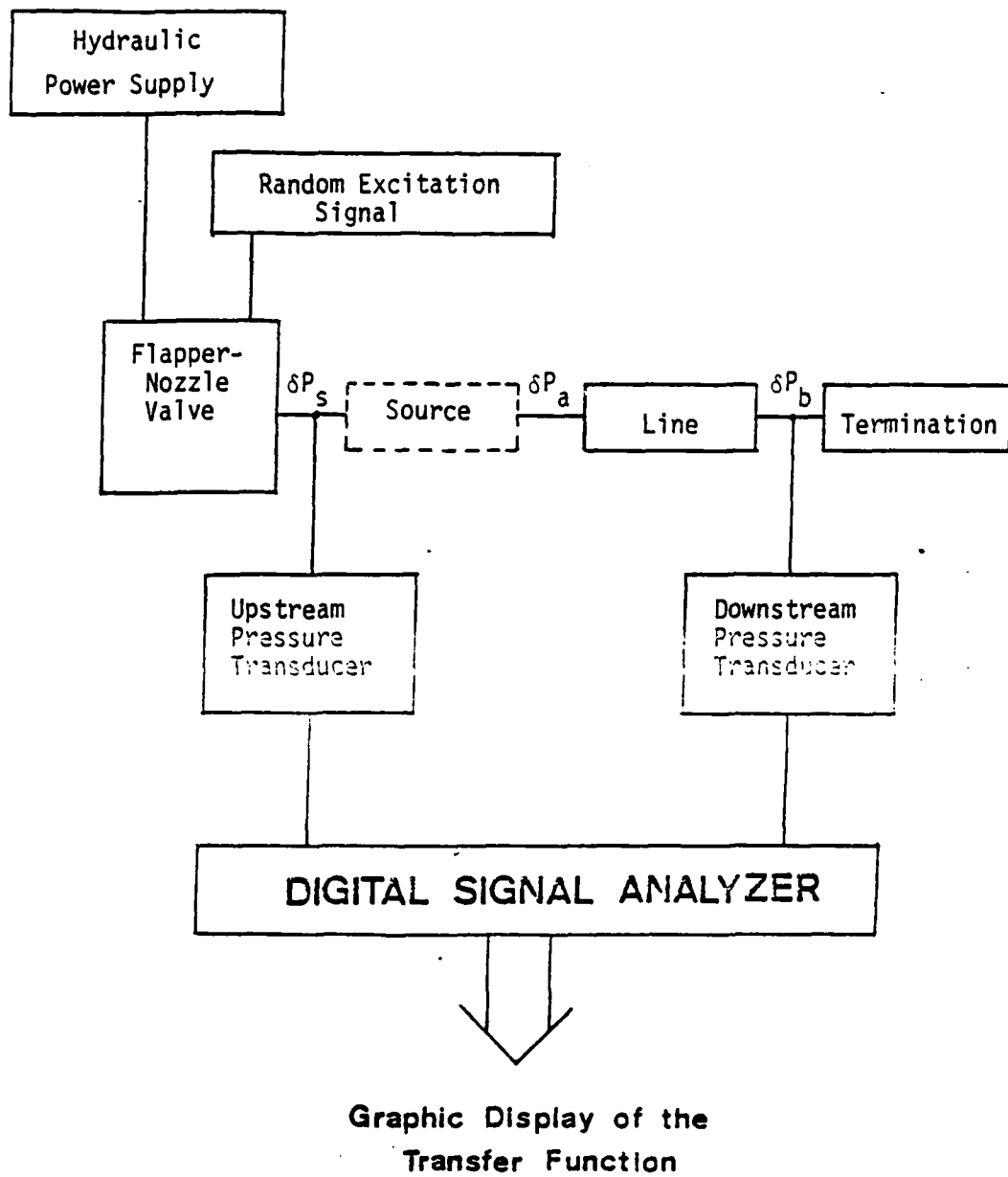


Fig. A1. Functional Block Diagram of the Experimental Apparatus

responses. Table A1 lists the effective line viscosity at different temperatures for the three different diameter lines used in the experiments.

### Equipment

A General Electric electric-to-fluidic Signal Generator was used to produce the pressure signals. The supply pressures to the electric-to-fluidic signal generator were 344.5 kPa (50 psi) and 689 kPa (100 psi) which result in mean operating signal levels of 193 kPa and 379 kPa respectively.

Dynamic pressures were measured with National Semiconductor differential pressure transducer model LX1820D and related signal conditioning equipment. A calibration of 10 psi per volt was used.

An accumulator was installed to minimize the pressure pulsation in the pressure supply; pieces of sponge were inserted between each coil of copper tubing to minimize the vibration of the line.

MIL-H-5606 was used as the hydraulic fluid.

Round copper tubing was used for the transmission lines. Three diameters were chosen, the inside diameters were 1.7 mm, 4.8 mm, and 7.6 mm. For each diameter, two to three lengths were used, ranging from 4.8 m to 14.8 m. Characteristics of these lines are listed in Table A2. Two source impedances and six load impedances were used. Their specifications are listed in Table A3.

Hewlett Packard Model 5420A Digital Signal Analyzer was used. The analyzer supplied a random electrical signal of a specified spectrum to the flapper-nozzle valve. It also received the analog pressure signals,

Table A1. Effective Line Viscosity for Different Temperatures

T \ d	$\nu_e (10^{-6} \frac{m^2}{s})$		
	1.7 mm	4.8 mm	7.6 mm
25° C	20	30	50
35° C	17	27	47
45° C	13	23	43

Table A2. Characteristics of Copper Lines (at 35° C)

d \ l	1.7 mm		4.8 mm			7.6 mm		
	4.8 m	9.6 m	4.8 m	9.6 m	14.8 m	4.8 m	9.6 m	14.8 m
$\omega_c$ (Hz)	44.4	22.2	44.4	22.2	14.4	44.4	22.2	14.4
$\omega_v$ (Hz)	30	30	6	6	6	4.1	4.1	4.1
$\zeta$	0.34	0.68	0.067	0.134	0.207	0.047	0.093	0.144
$Z_o$ (M $\Omega$ hm)	498.9	498.9	62.6	62.6	62.6	25	25	25
$R_c$ (M $\Omega$ hm)	337	674	8.4	16.8	25.9	2.3	4.6	7.2
$L_c$ (MHenry)	1.79	3.57	0.224	0.448	0.691	0.089	0.179	0.276
$C_c$ (pF)	7.26	14.5	57.9	115.8	178.5	145.2	290.3	447.6

Table A3. Characteristics of Resistors Used for Load and Source Impedances (at 35°C)

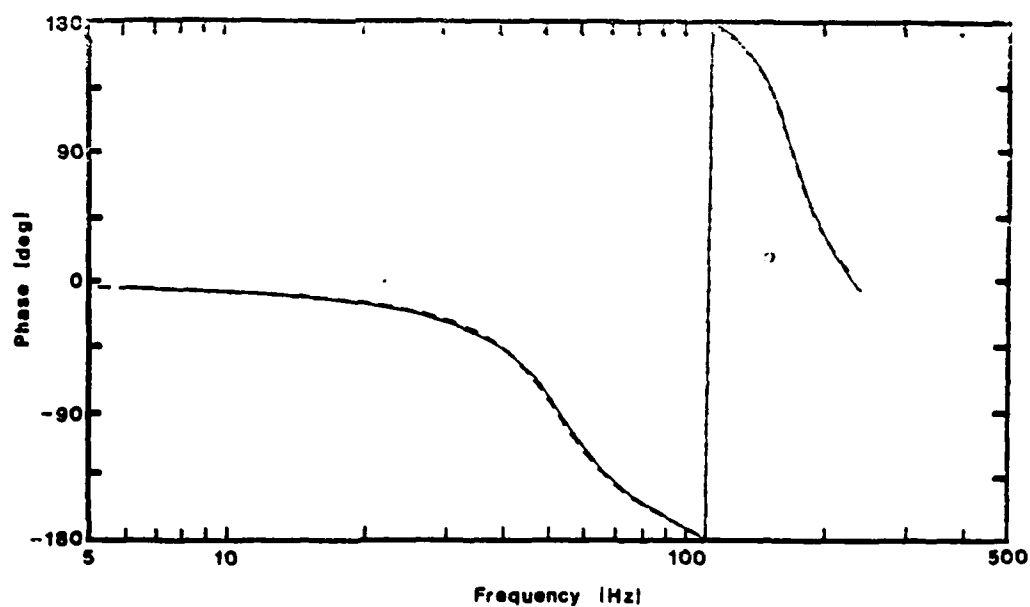
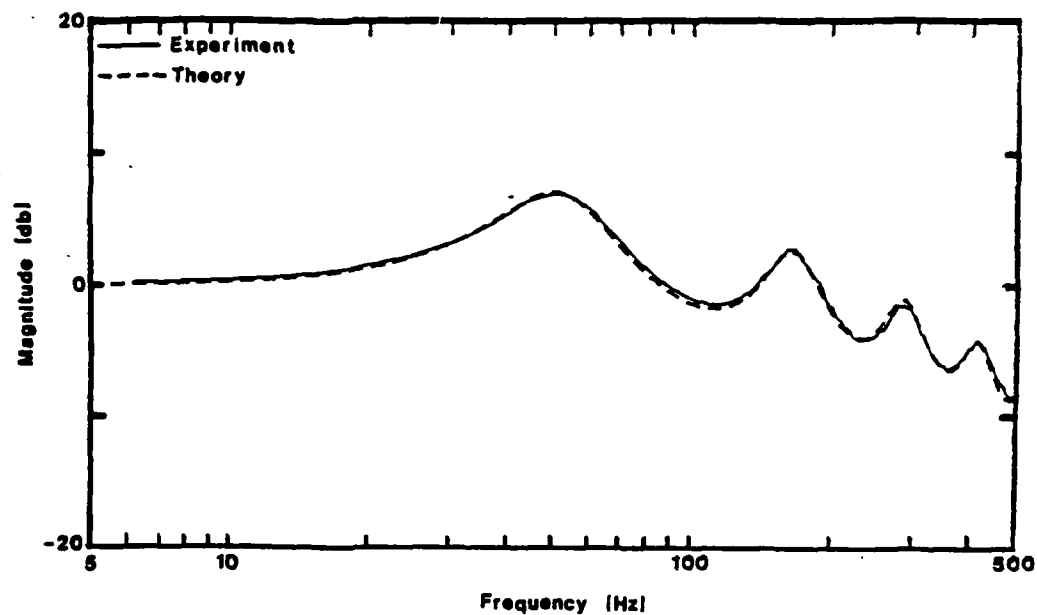
No.	Usage	$l$ (mm)	$d$ (mm)	No. of Tubes	$R$ (M $\Omega$ hm)	$L$ (MHenry)	$\omega_c$ (Hz)	$\omega_v$ (Hz)	$\zeta$
#1	Source	53	0.716	1	100	0.112	4084	199	0.024
#2	Source	53	0.716	4	25	0.028	4084	199	0.024
#3	Load	24.2	0.427	1	400	0.144	8944	559	0.031
#4	Load	50	0.716	1	92	0.105	4329	199	0.023
#5	Load	52	0.716	4	23	0.0275	4163	199	0.024
#6	Load	297	0.88	1	290	0.415	729	132	0.091
#7	Load	290	1.63	1	22	0.118	746	38	0.025
#8	Load	315	2.37	1	5	0.061	687	18	0.013

converted them to digital signals, and computed the transfer function.

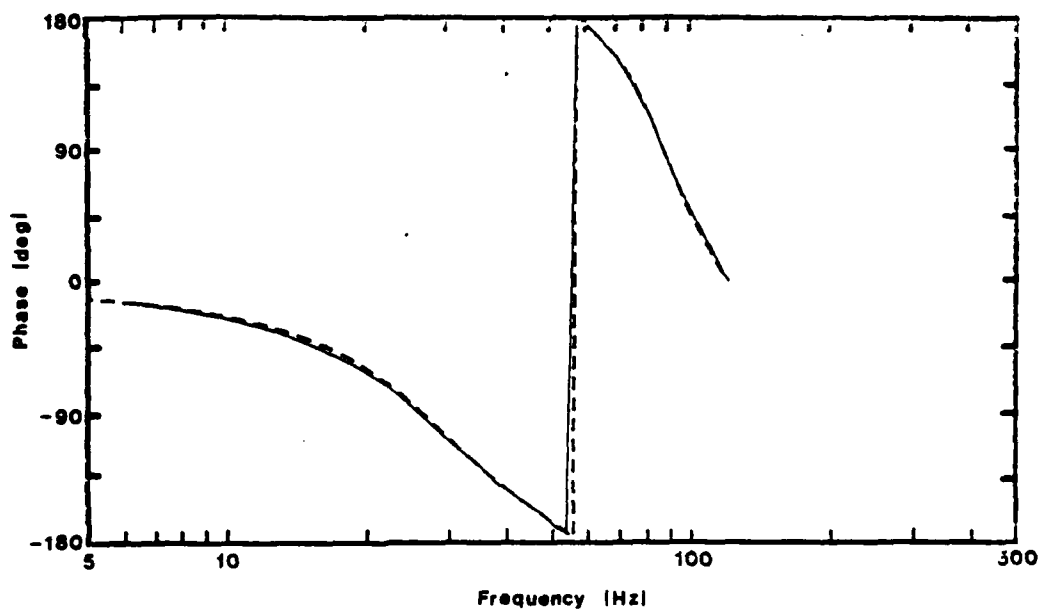
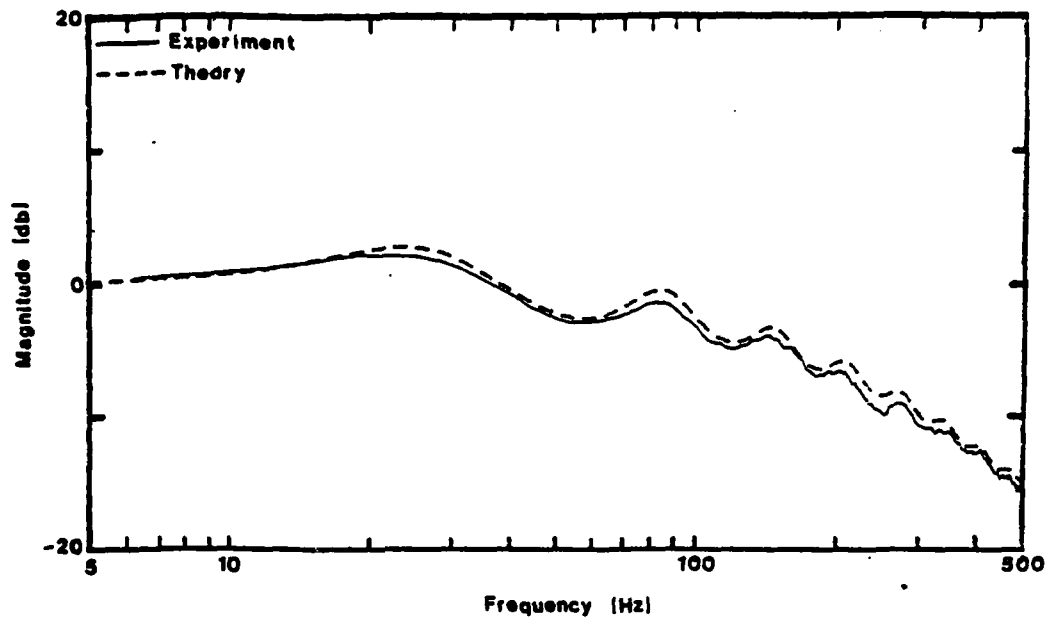
#### Quality of Results

The experimental frequency response generated with the procedure and equipment described above is an excellent standard for comparison. The response indicates multiple resonances and nonminimum phase which is expected from a distributed parameter system. The results are given in the following pages where they are compared directly with the analytical predictions.

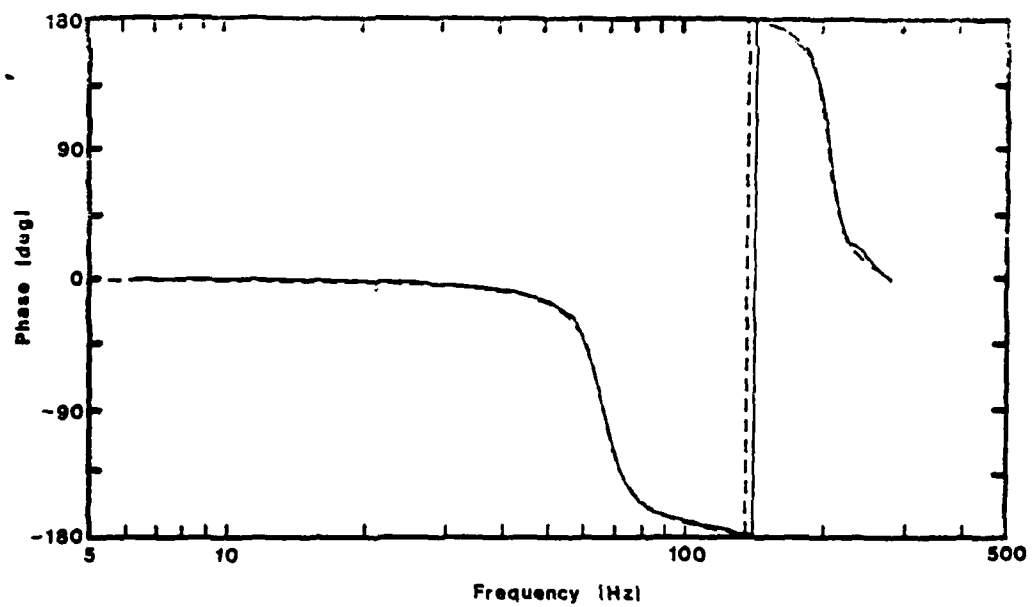
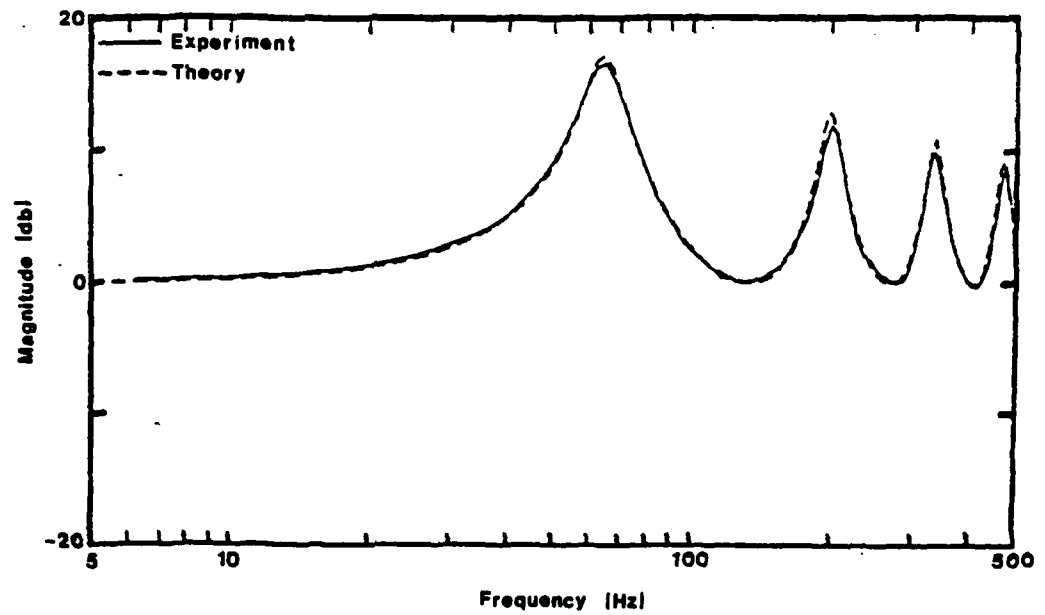
The minor discrepancies between the data and the analytical predictions can be explained by the following factors. Firstly, the bandwidth of the flapper-nozzle valve is 400 Hz, therefore frequencies higher than 400 Hz, will have a very attenuated signal so that accuracy is reduced. Secondly, the fluid viscosity is very sensitive to temperature variations, thus the viscosity used in obtaining the theoretical responses may include slight inaccuracies. Thirdly, the minor losses associated with expansion and contraction of flow passage is not considered in the theoretical model. The error exhibited in the magnitude or phase of the transfer function is very small.



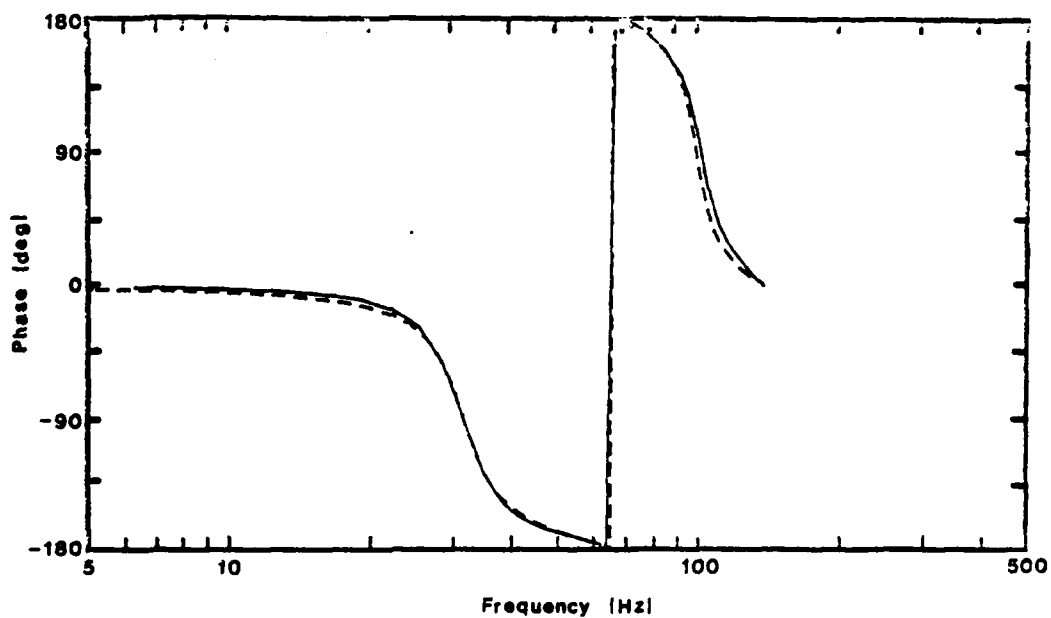
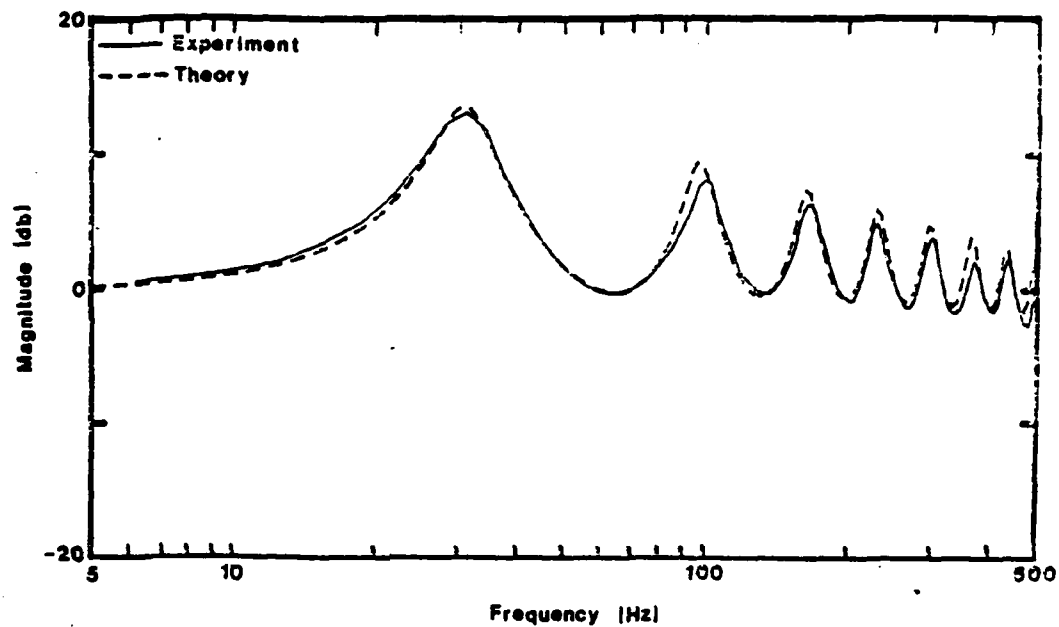
Data Set 1. Line with Blocked Termination  
( $\ell = 4.8$  m,  $d = 1.7$  mm)



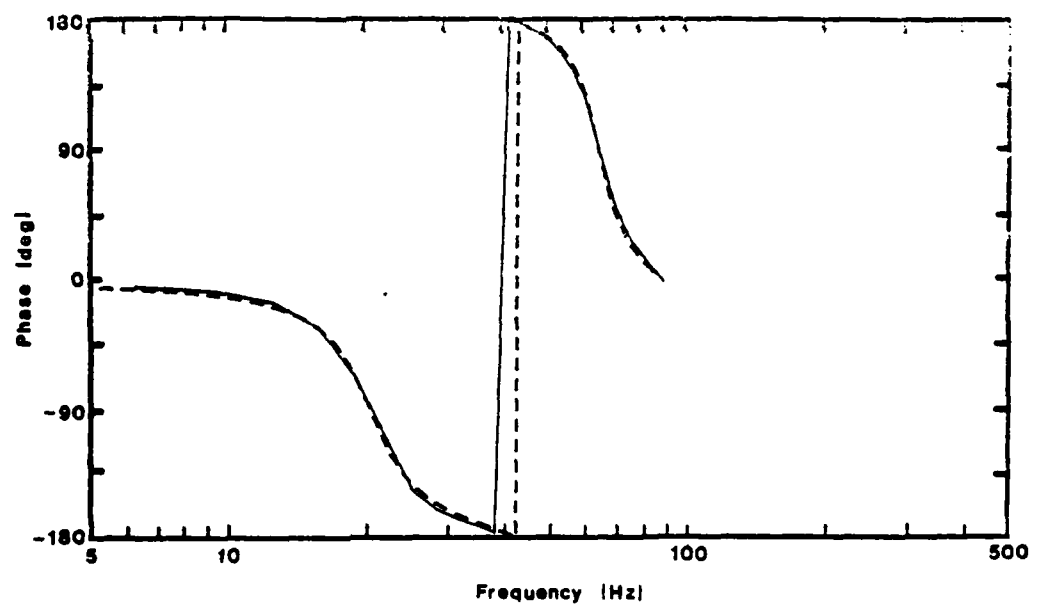
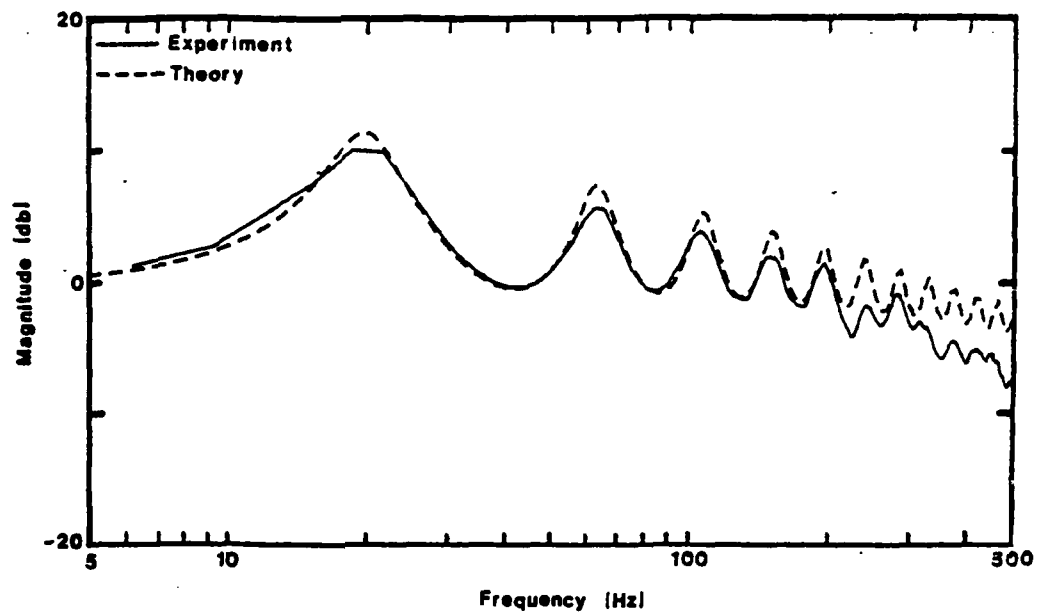
Data Set 2. Line with Blocked Termination  
( $\lambda = 9.6$  m,  $d = 1.7$  mm)



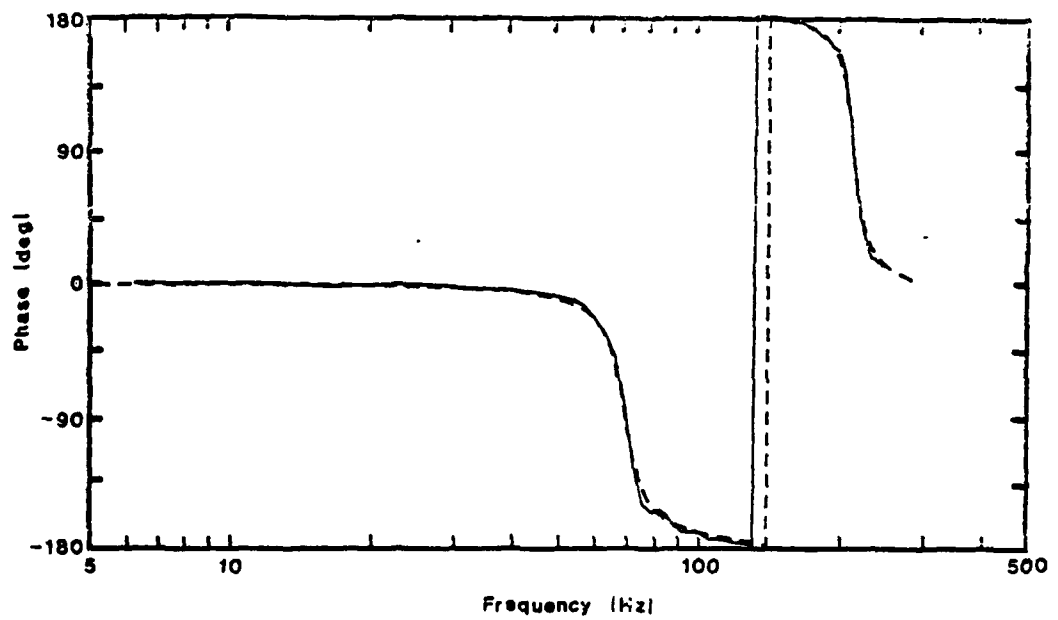
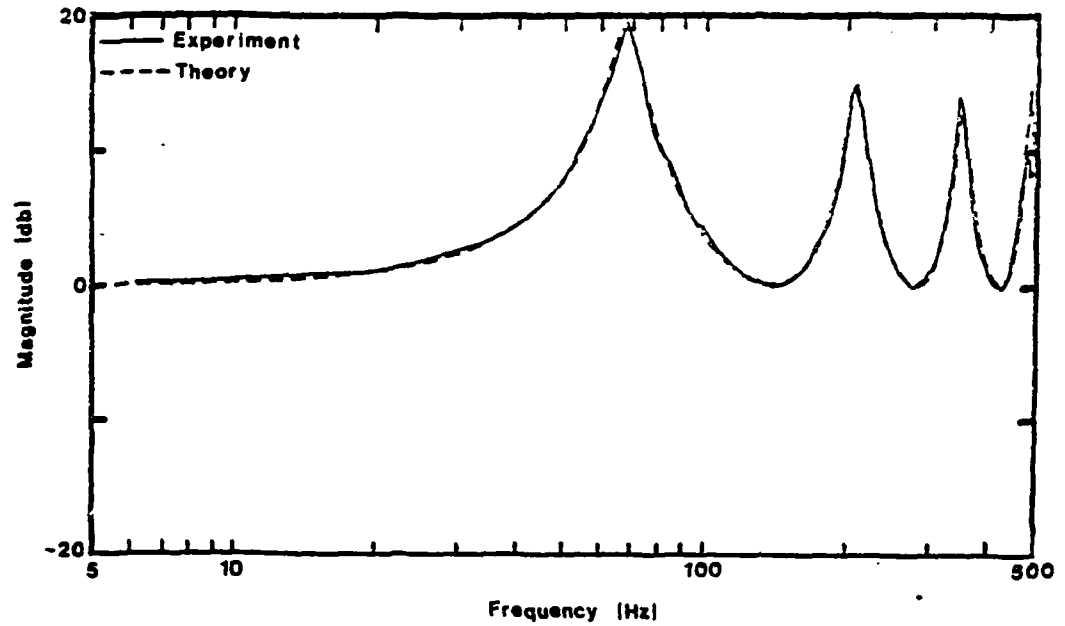
Data Set 3. Line with Blocked Termination  
( $\ell = 4.8$  m,  $d = 4.8$  mm)



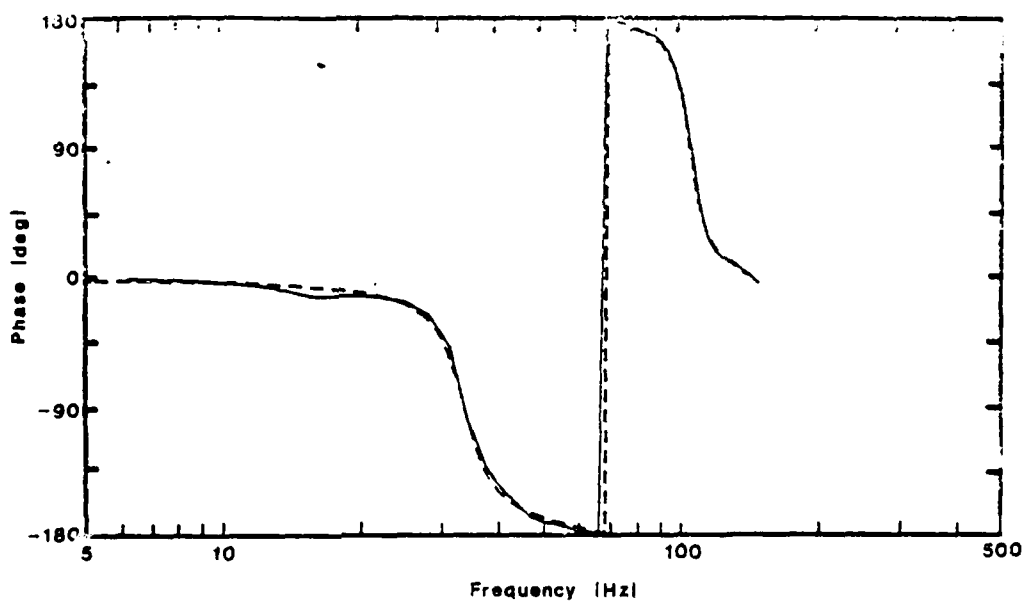
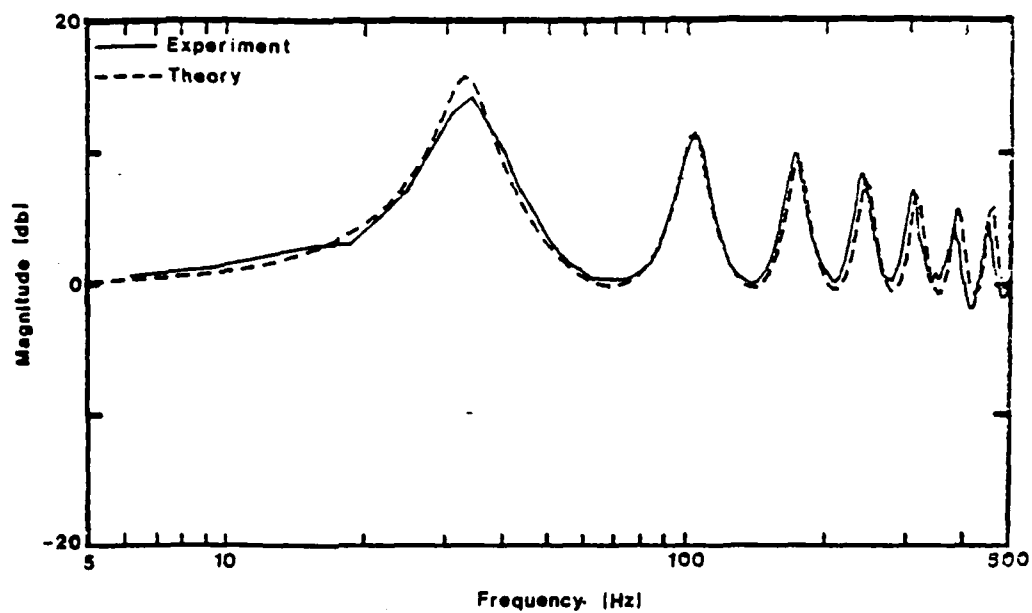
Data Set 4. Line with Blocked Termination  
( $l = 9.6$  m,  $d = 4.8$  mm)



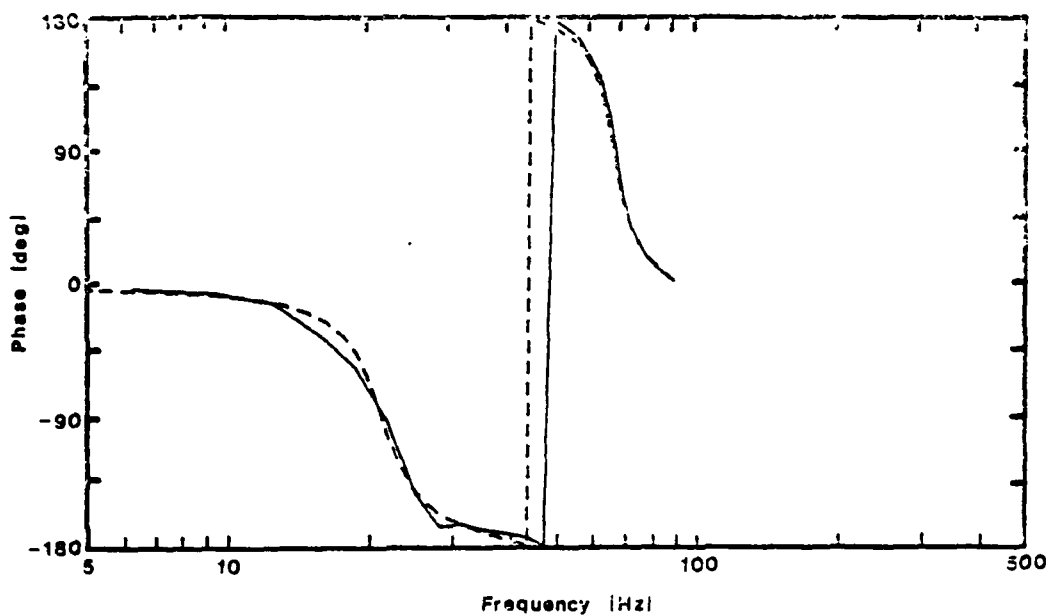
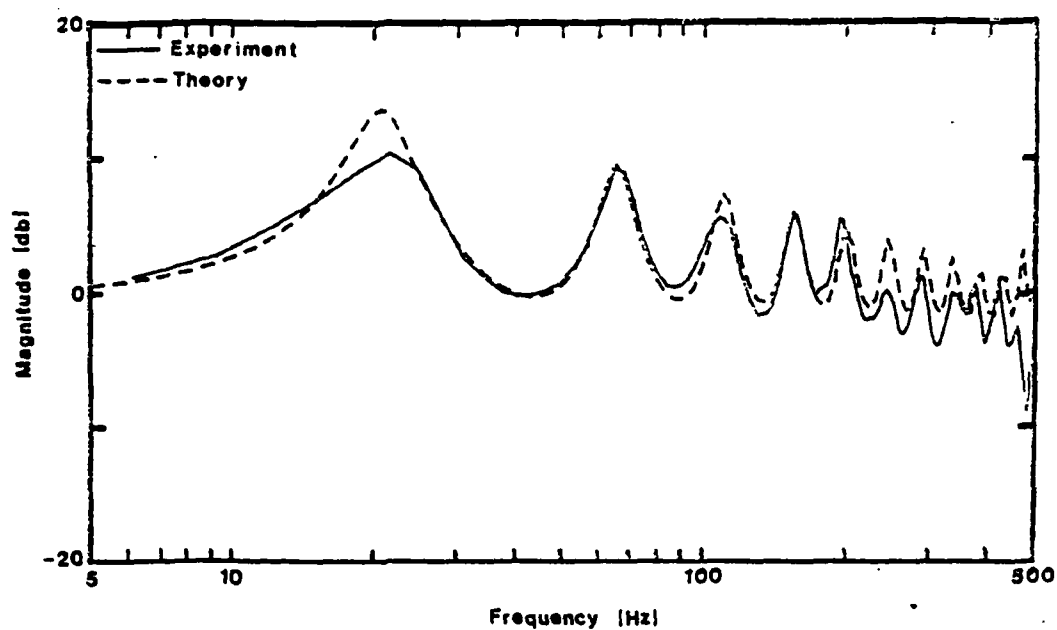
Data Set 5. Line with Blocked Termination  
( $\lambda = 14.8$  m,  $d = 4.8$  mm)



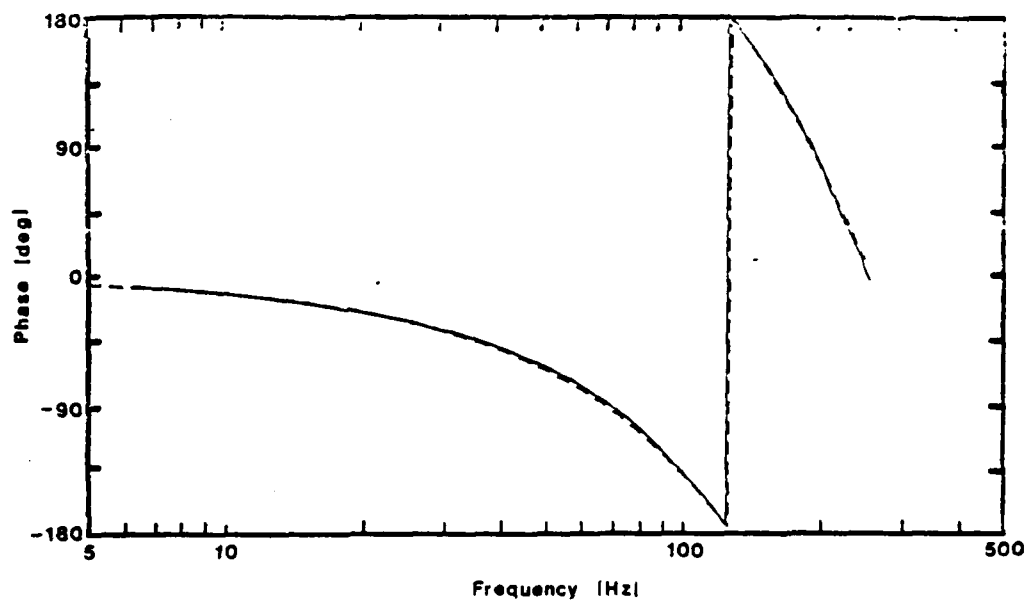
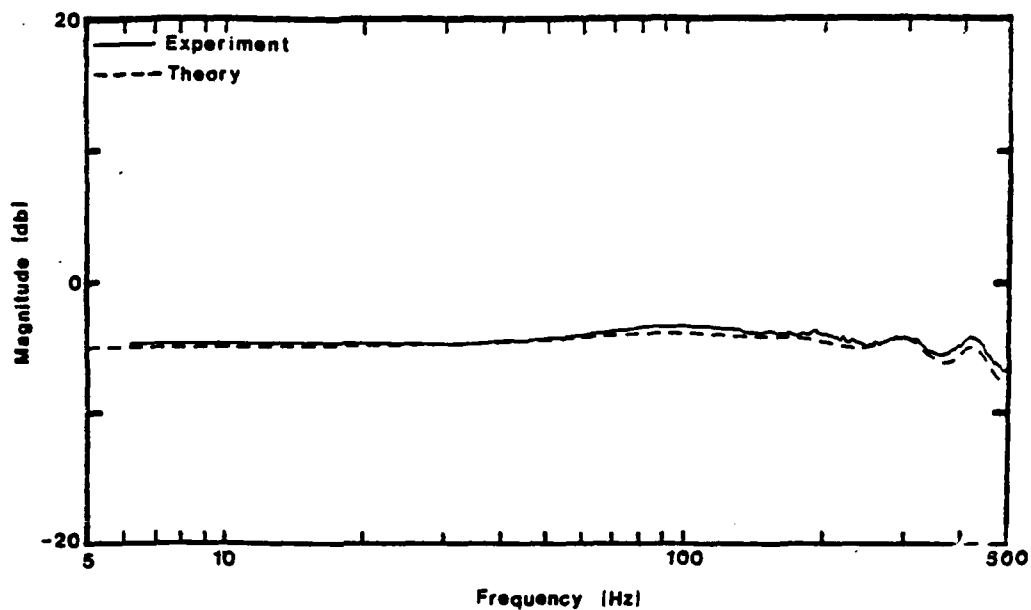
Data Set 6. Line with Blocked Termination  
( $\lambda = 4.8$  m,  $d = 7.6$  mm)



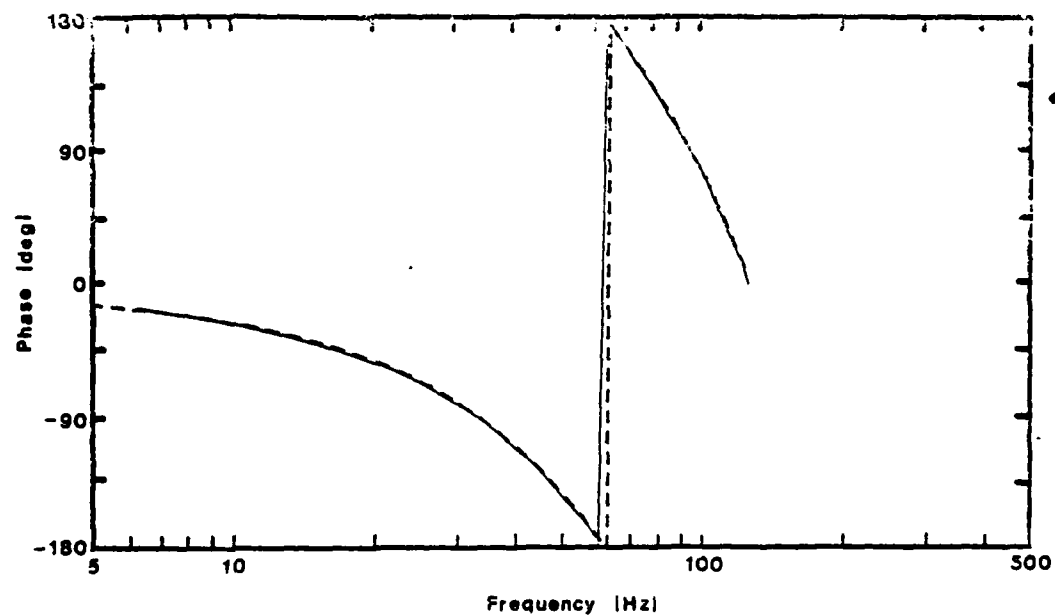
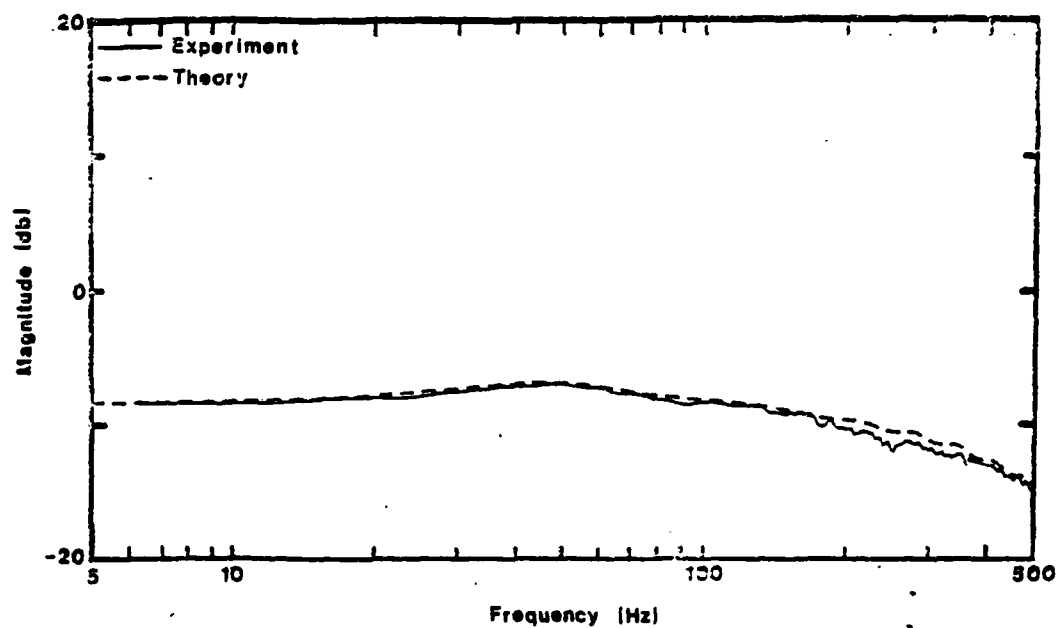
Data Set 7. Line with Blocked Termination  
( $\lambda = 9.6$  m,  $d = 7.6$  mm)



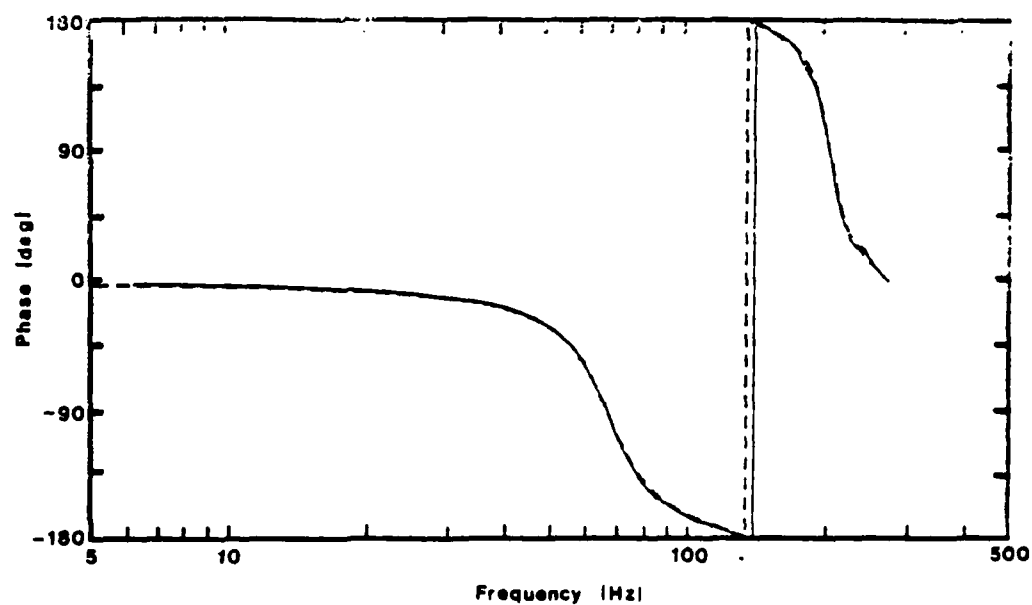
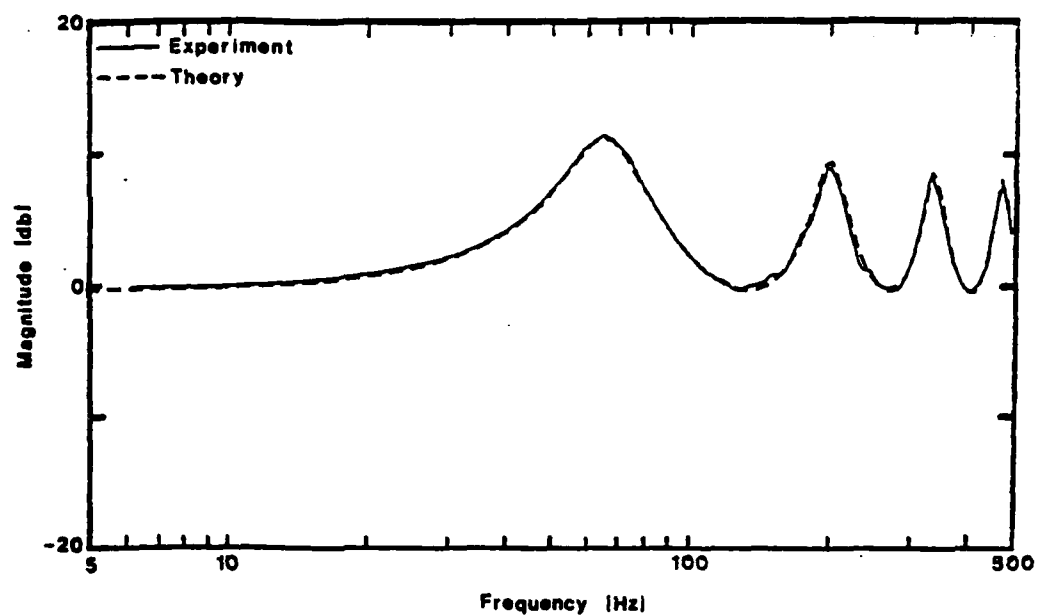
Data Set 8. Line with Blocked Termination  
( $\lambda = 14.8$  m,  $d = 7.6$  mm)



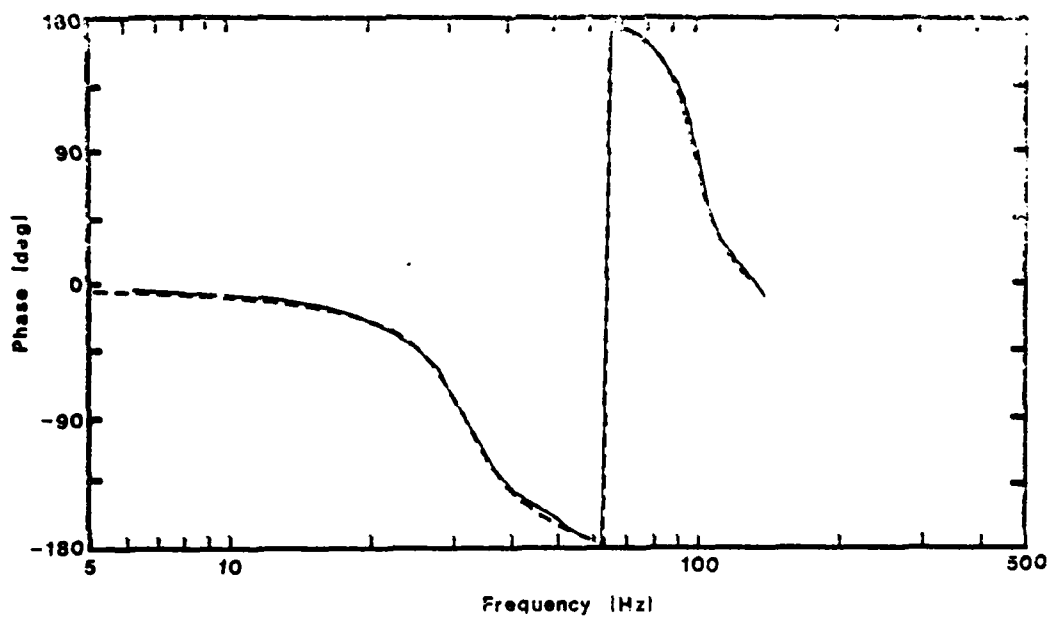
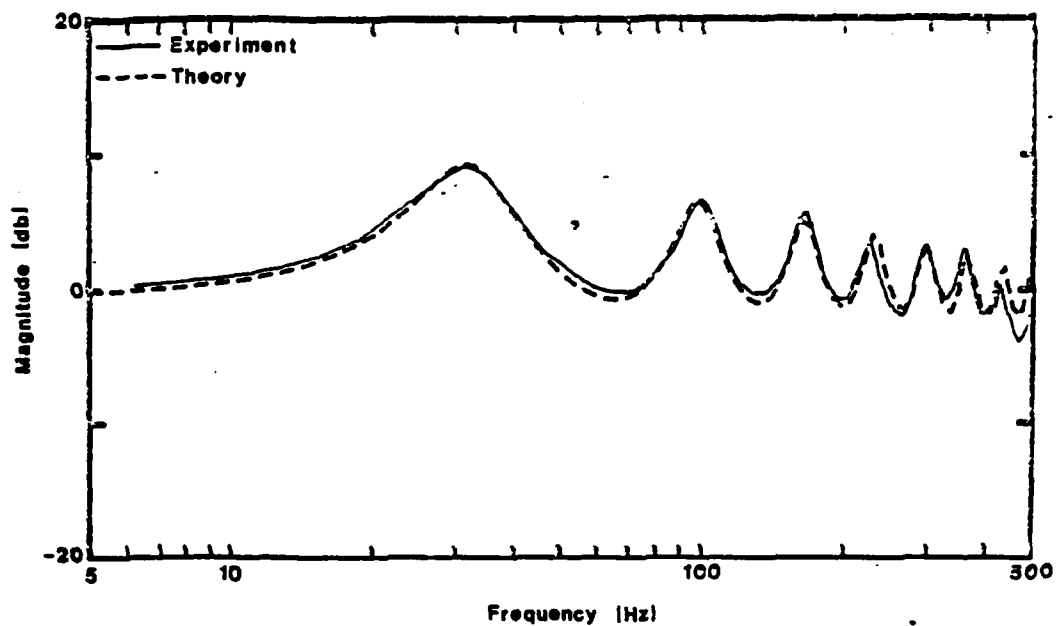
Data Set 9. Line with Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



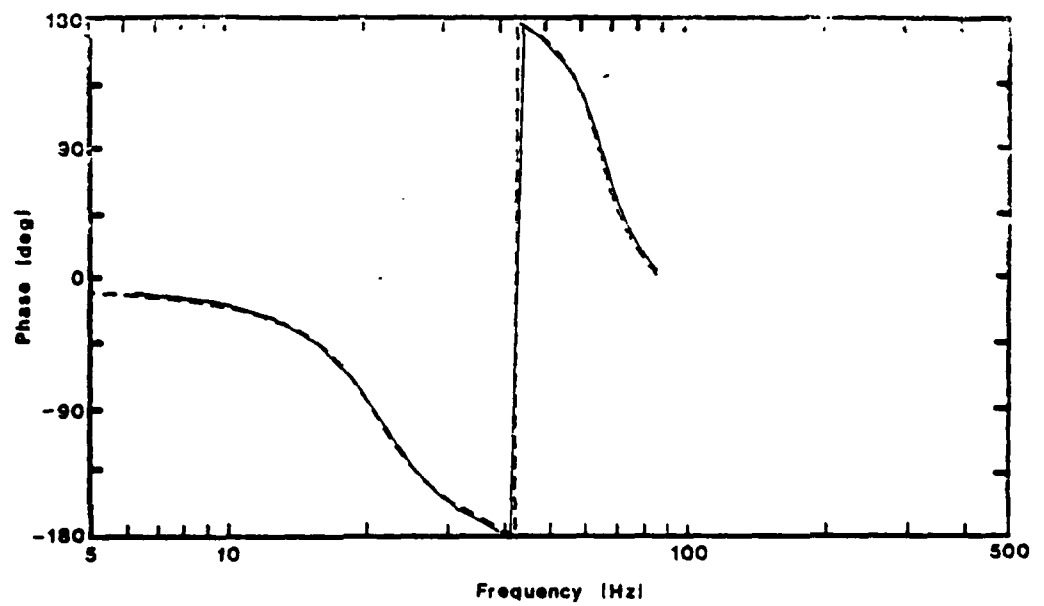
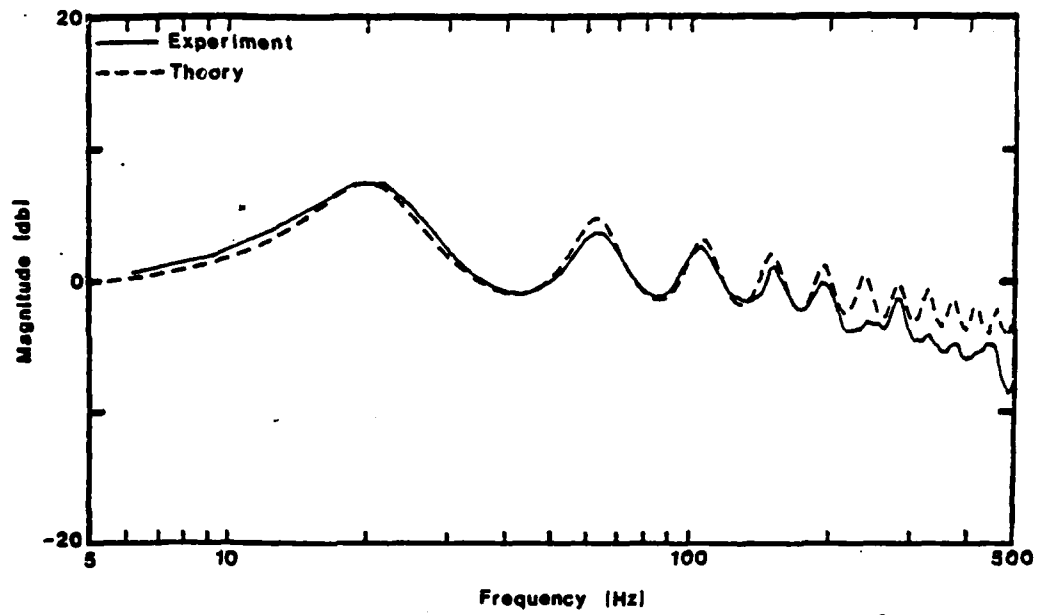
Data Set 10. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



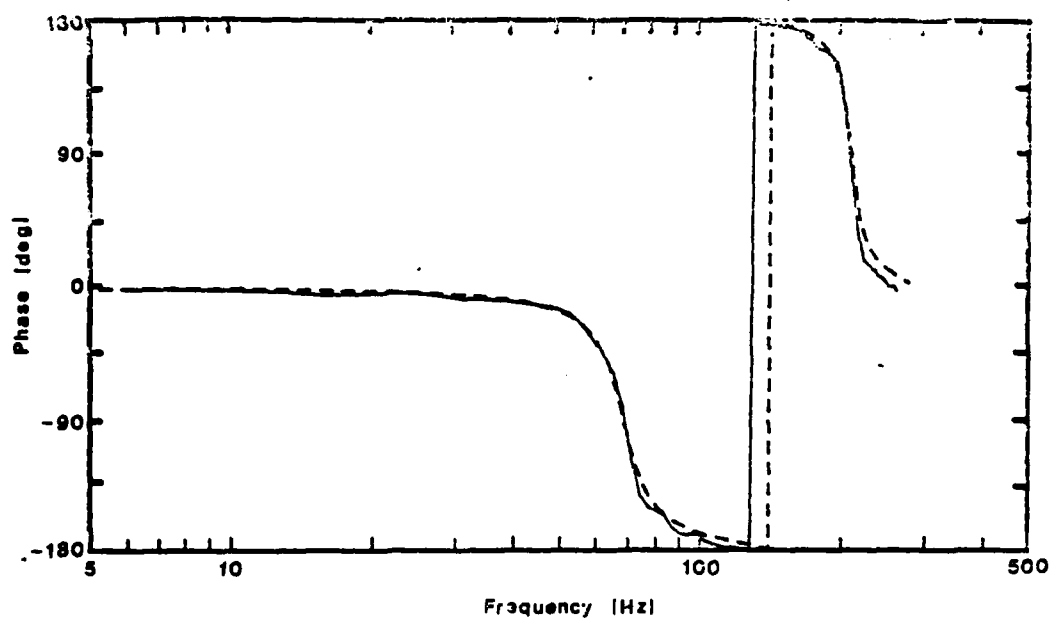
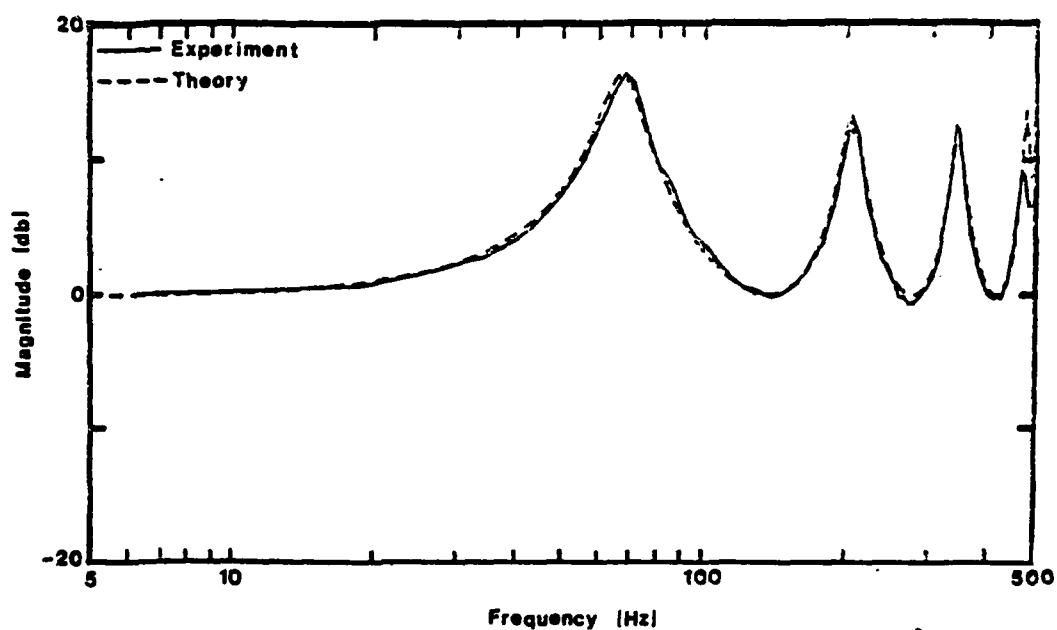
Data Set 11. Line with Load Impedance  
( $\lambda = 4.8$  m,  $d = 4.8$  mm; Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



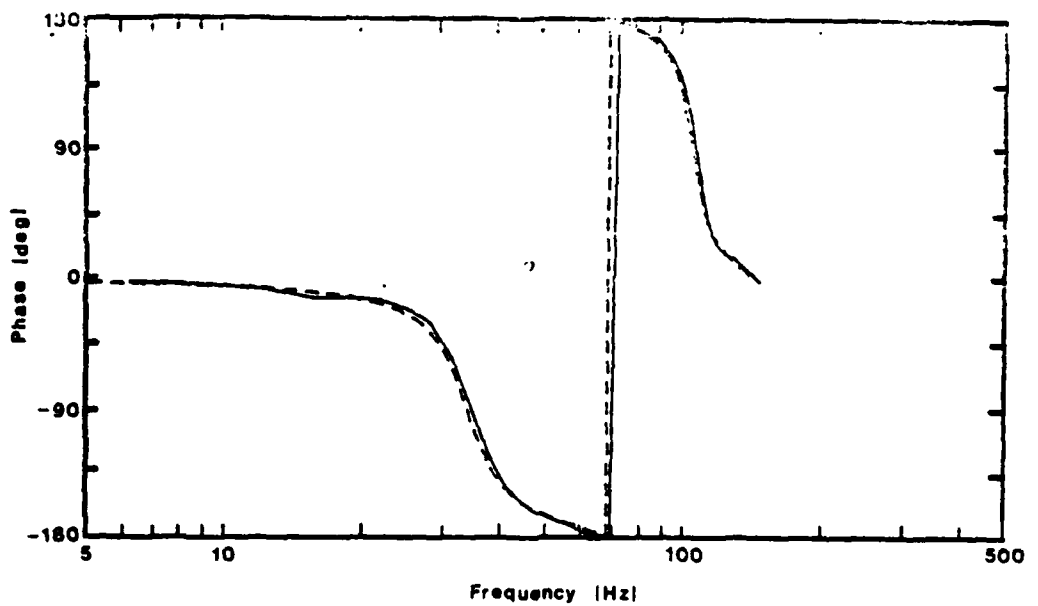
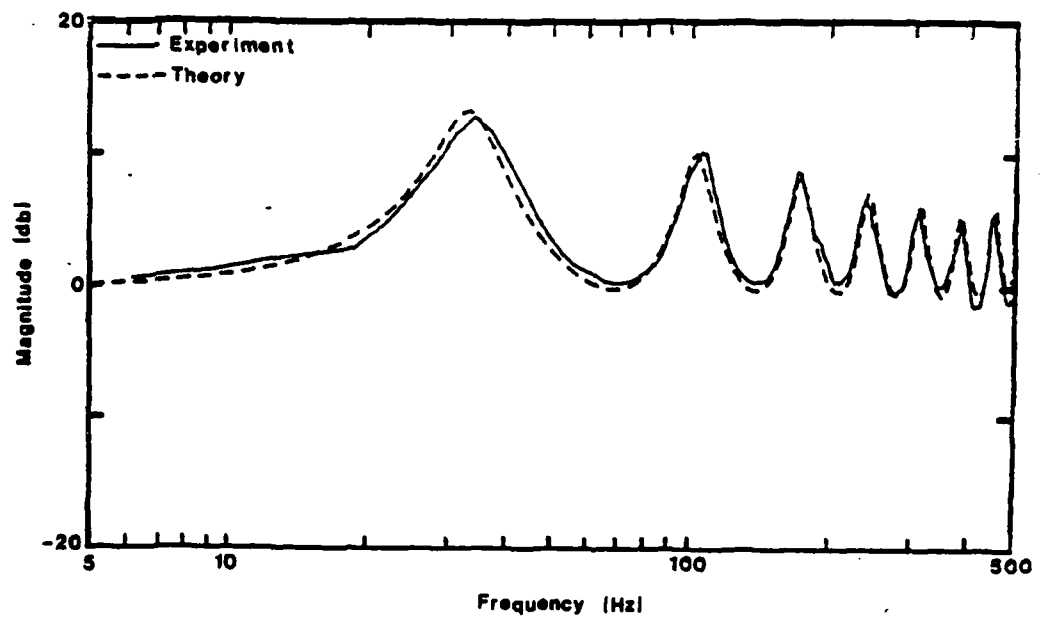
Data Set 12. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



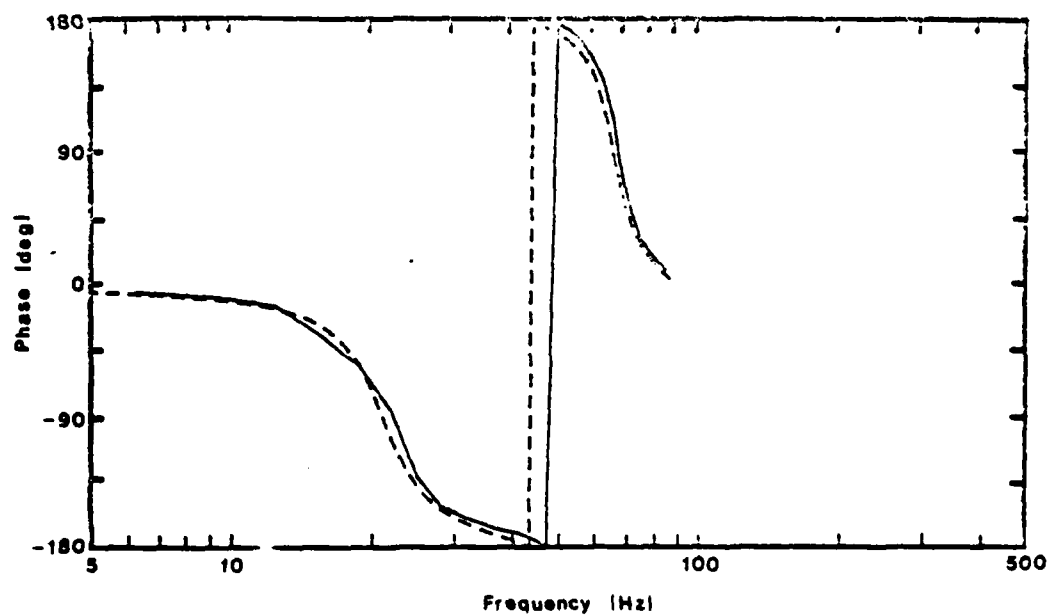
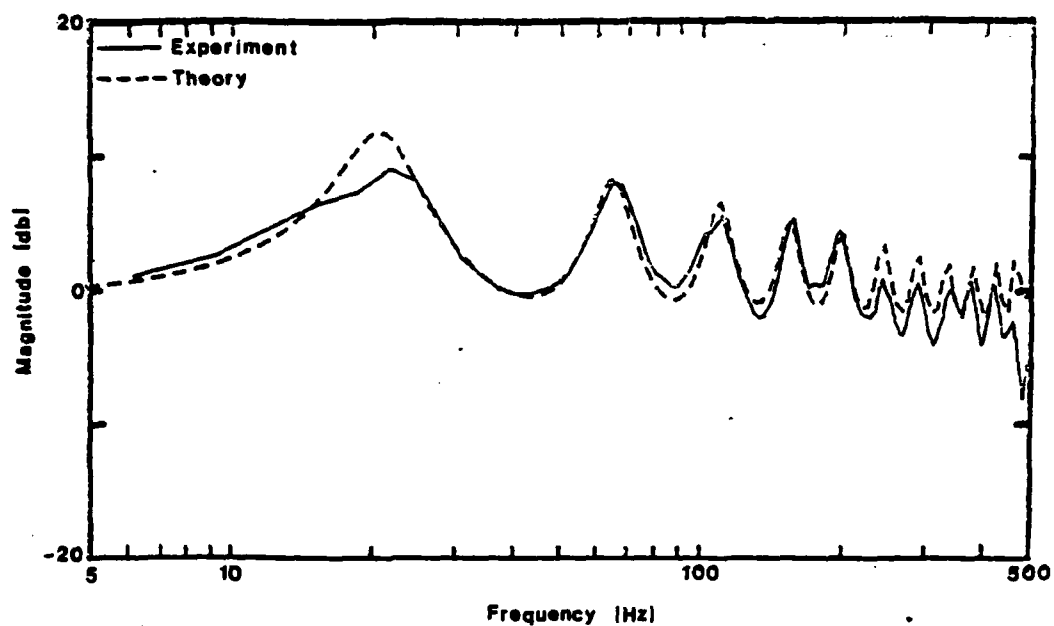
Data Set 13. Line with Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



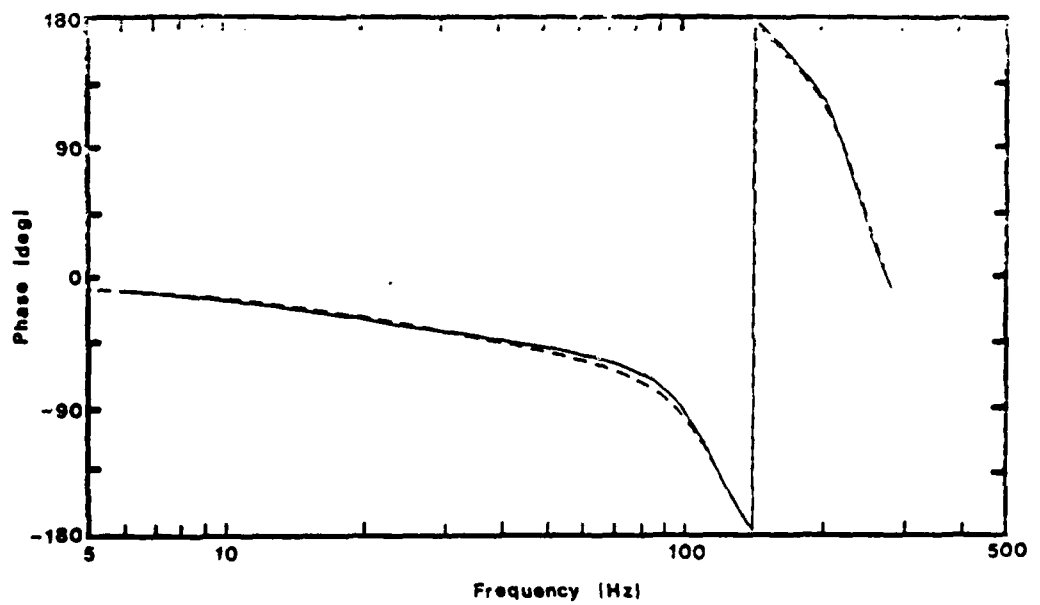
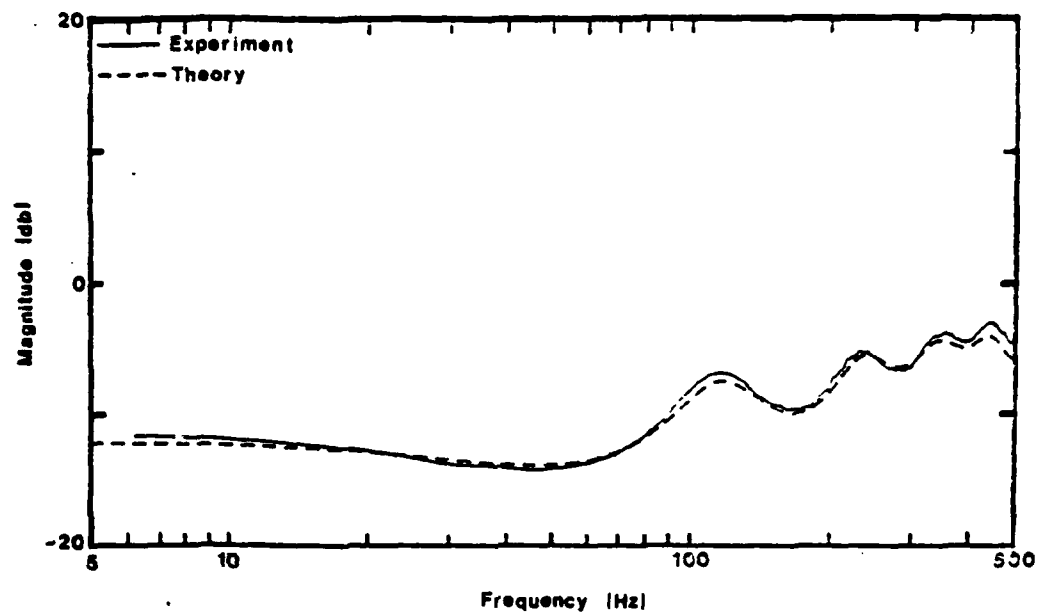
Data Set 14. Line with Load Impedance  
 $\ell = 4.8$  m,  $d = 7.6$  mm; Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



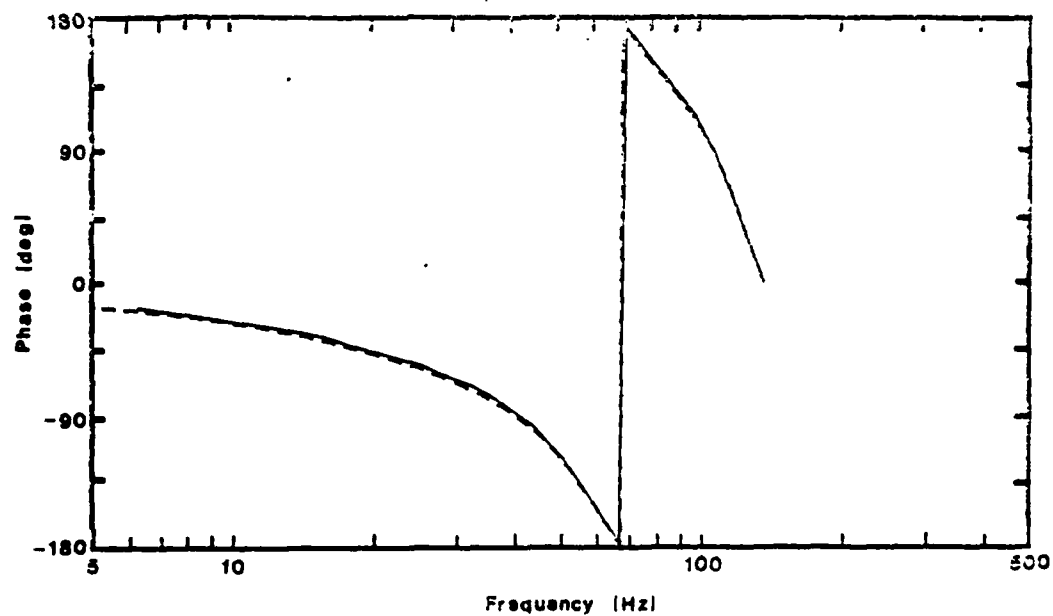
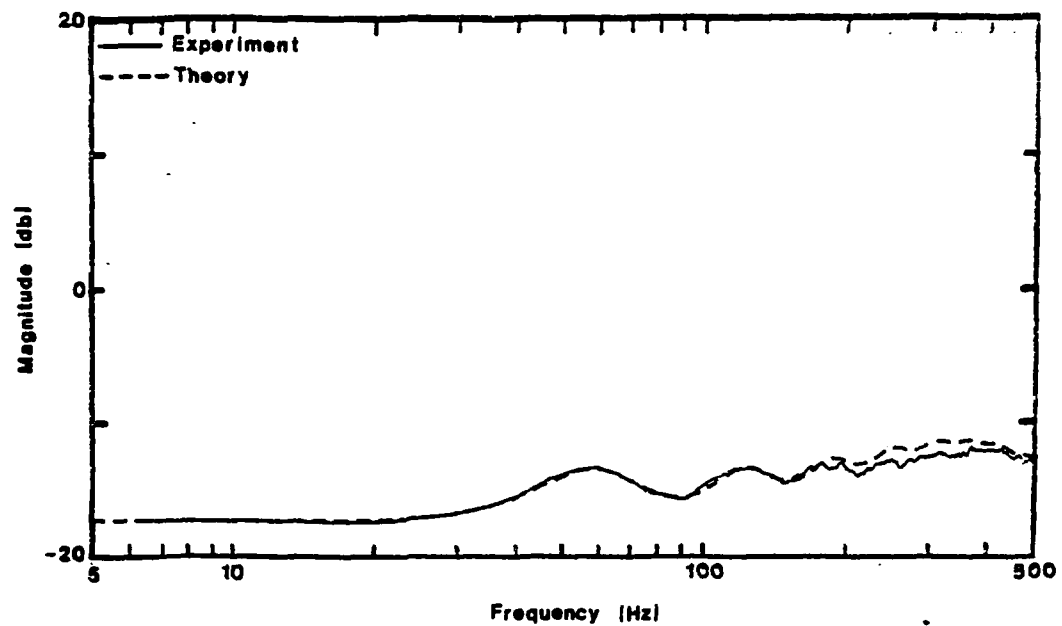
Data Set 15. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



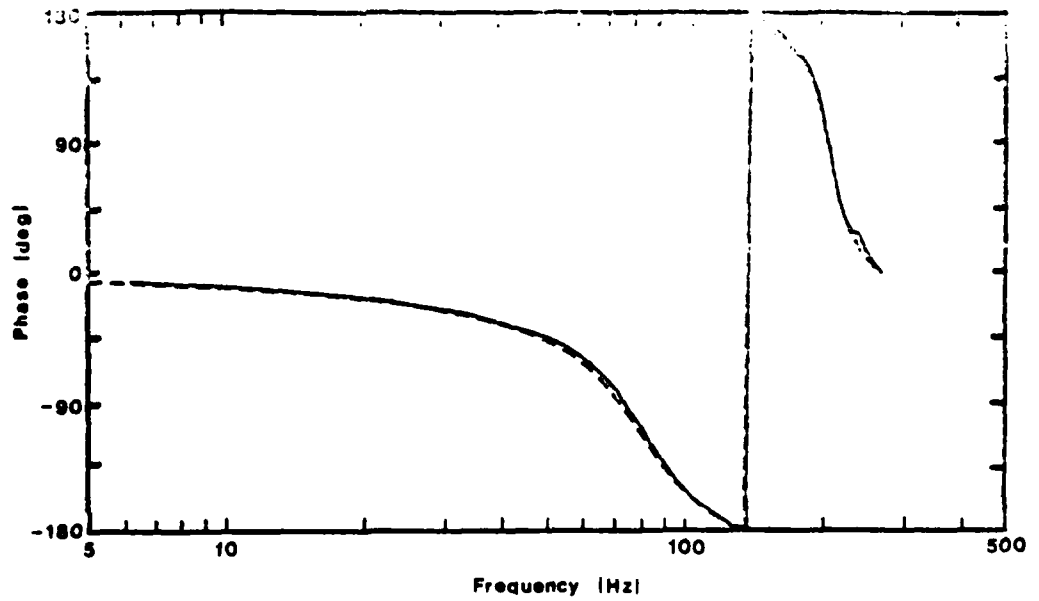
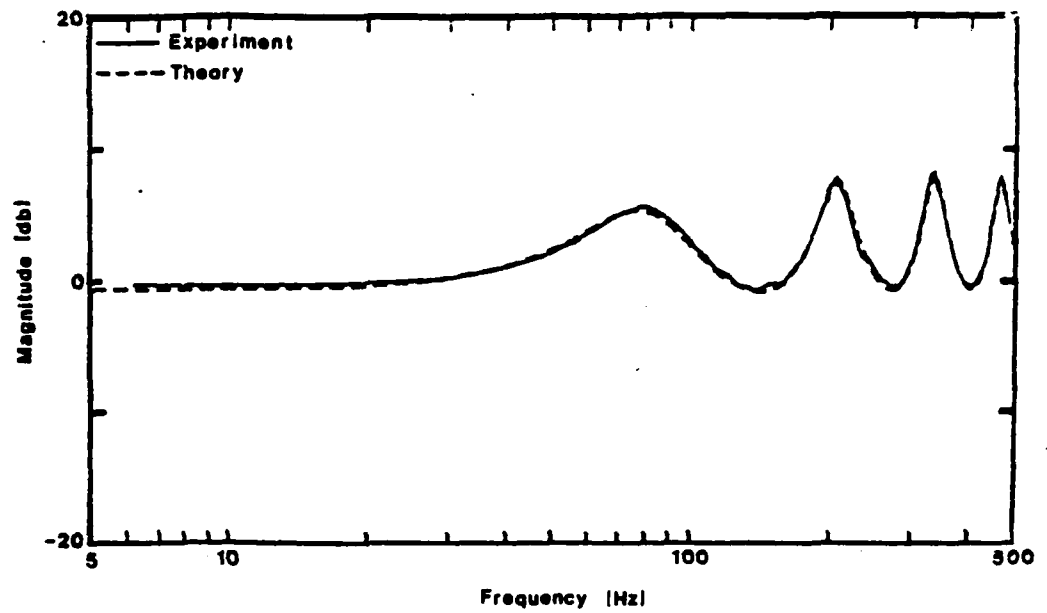
Data Set 16. Line with Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



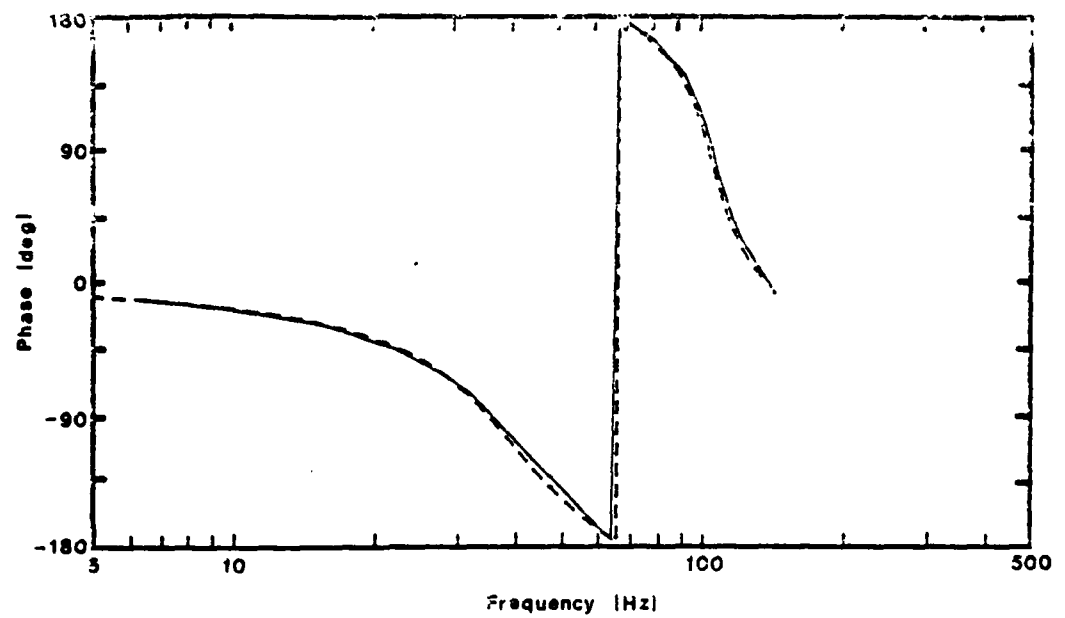
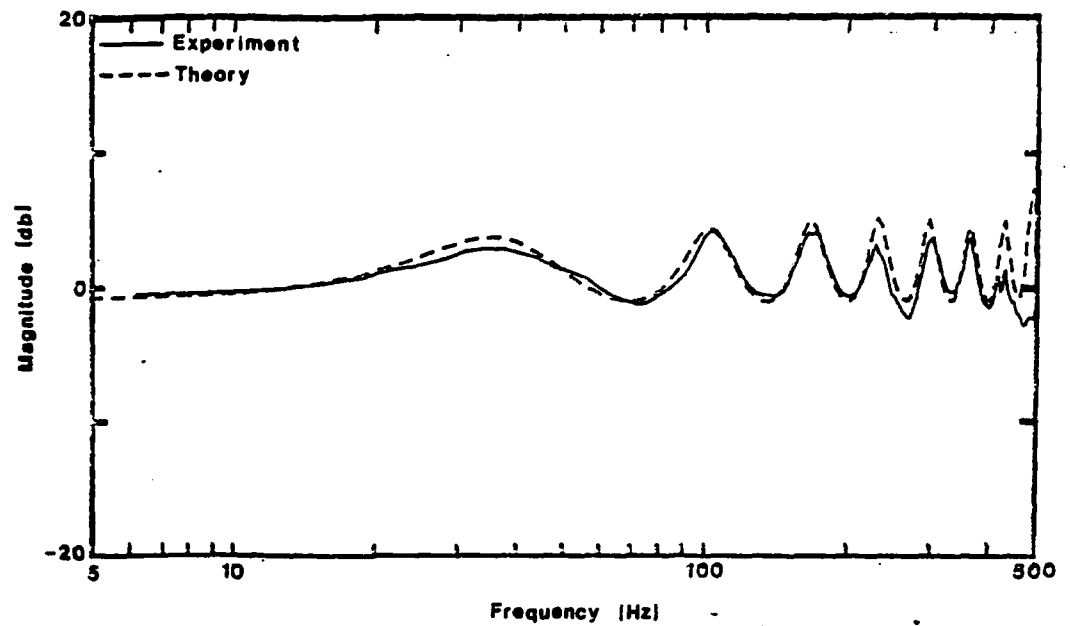
Data Set 17. Line with Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



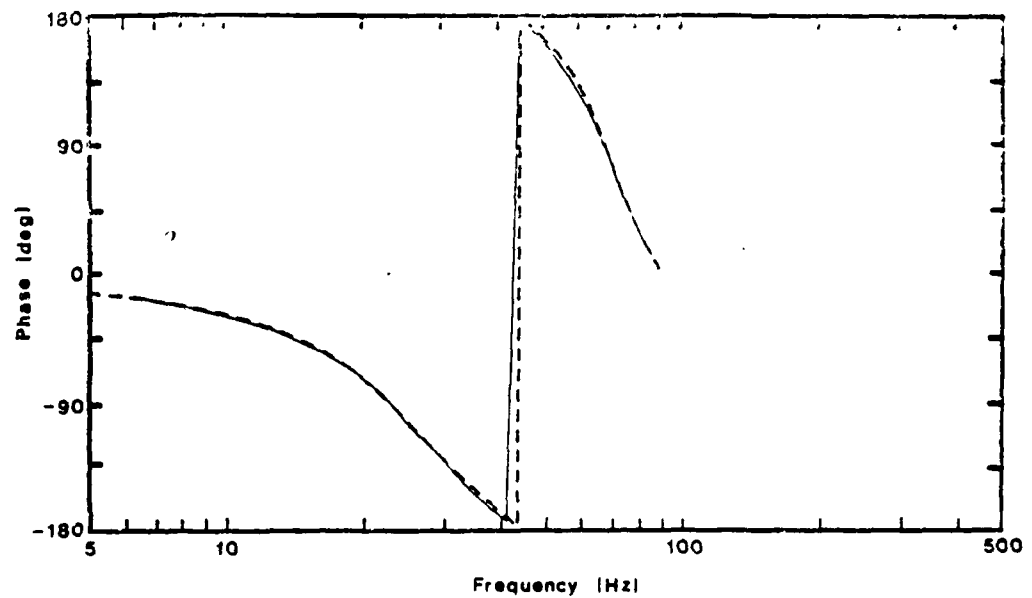
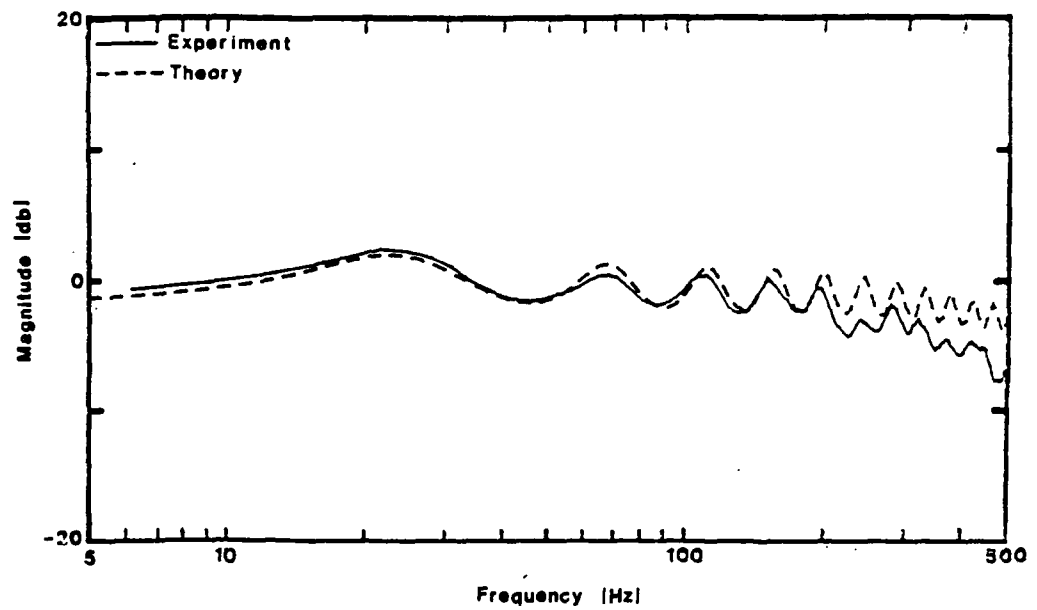
Data Set 18. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 1.7$  mm; Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



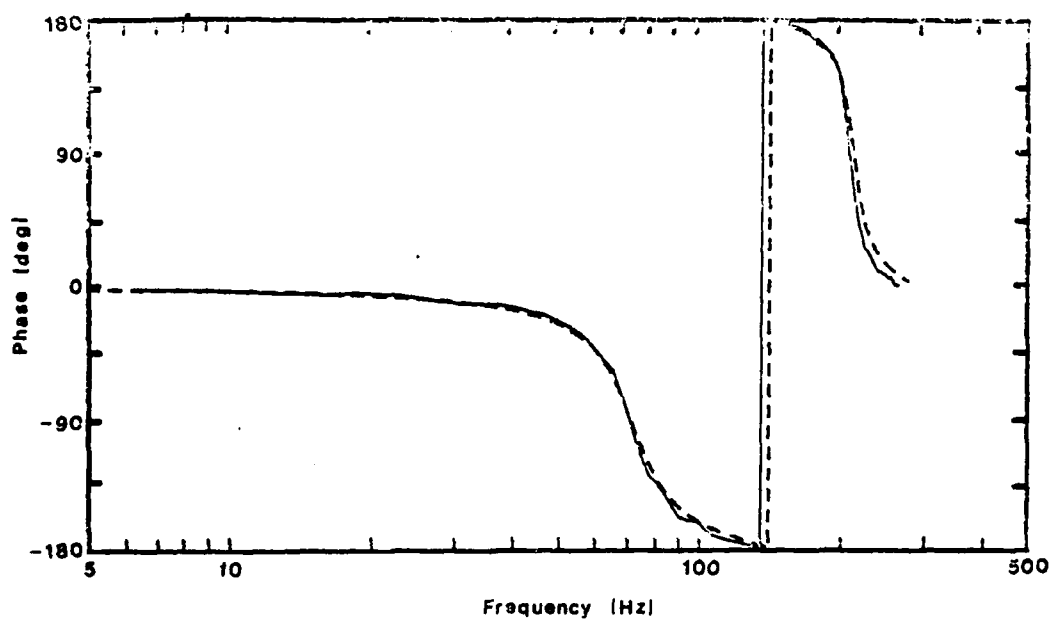
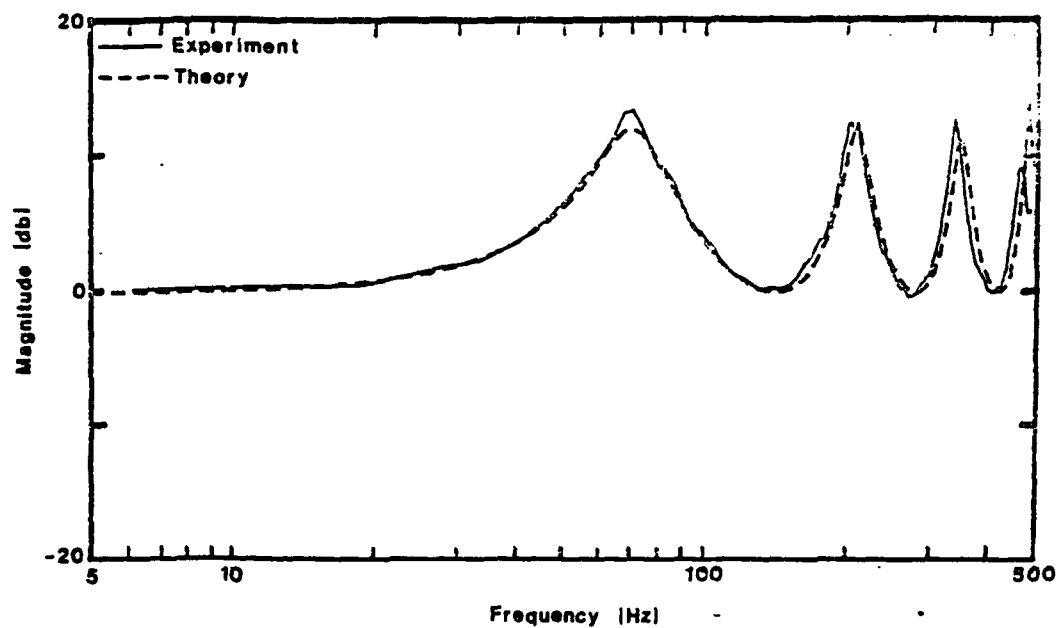
Data Set 19. Line with Load Impedance  
 ( $l = 4.8$  m,  $d = 4.8$  mm; Resistor #4,  $l = 50$  mm,  $d = .716$  mm)



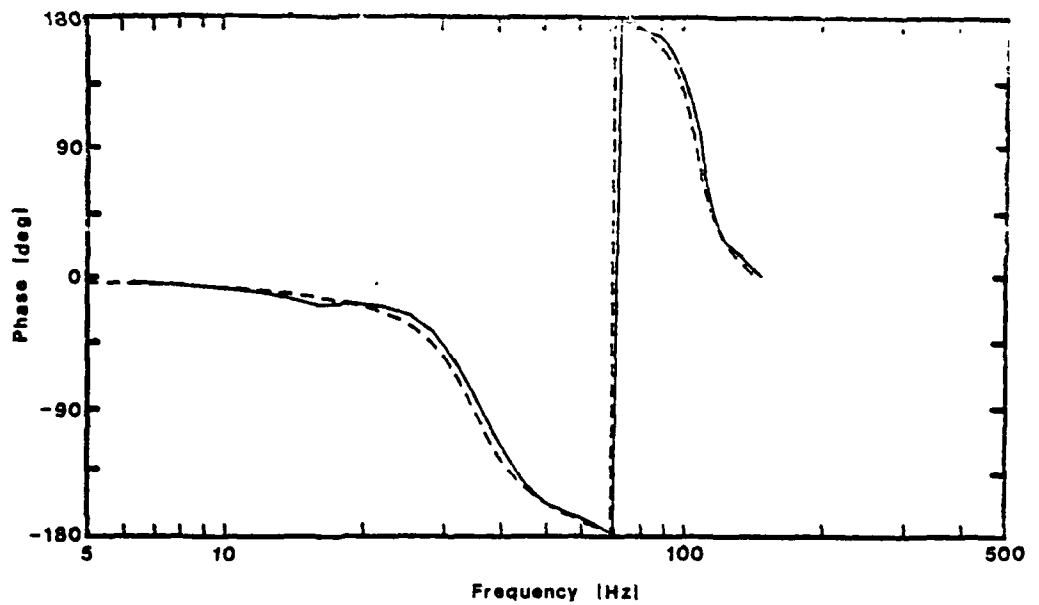
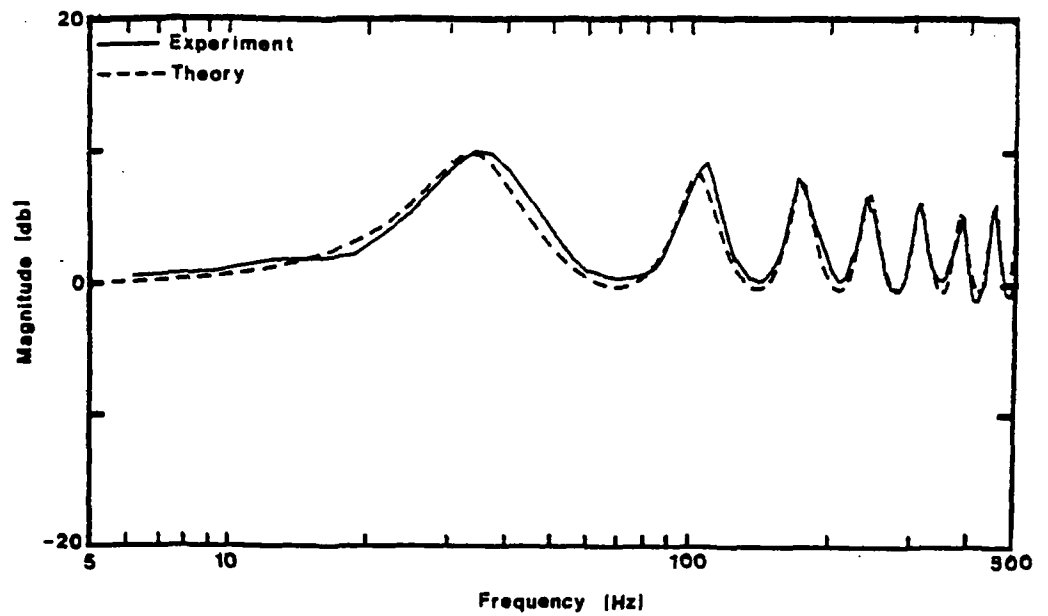
Data Set 20. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 4.8$  mm; Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



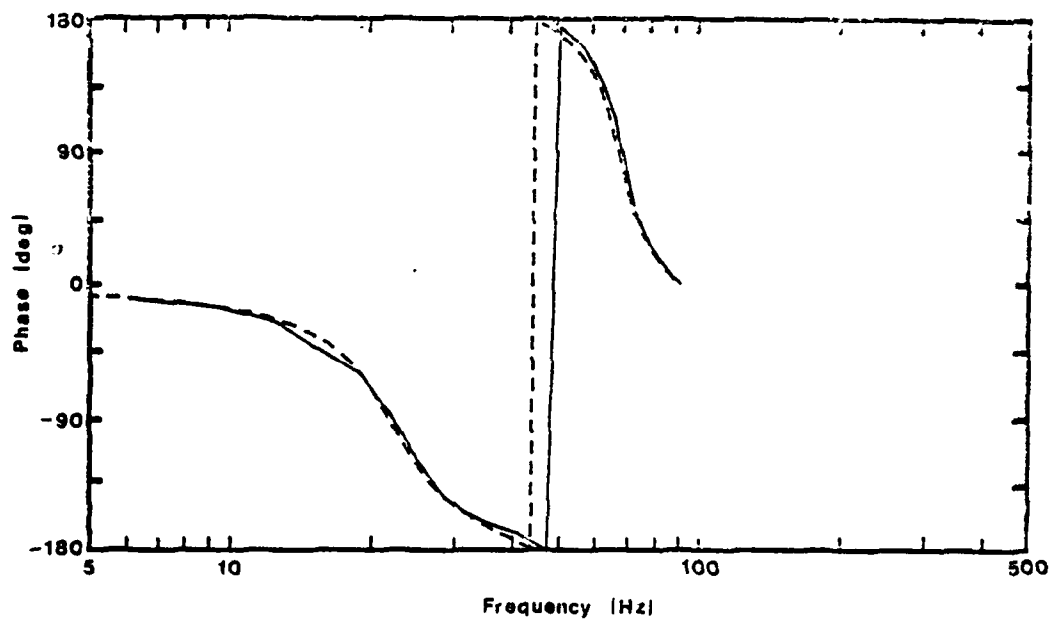
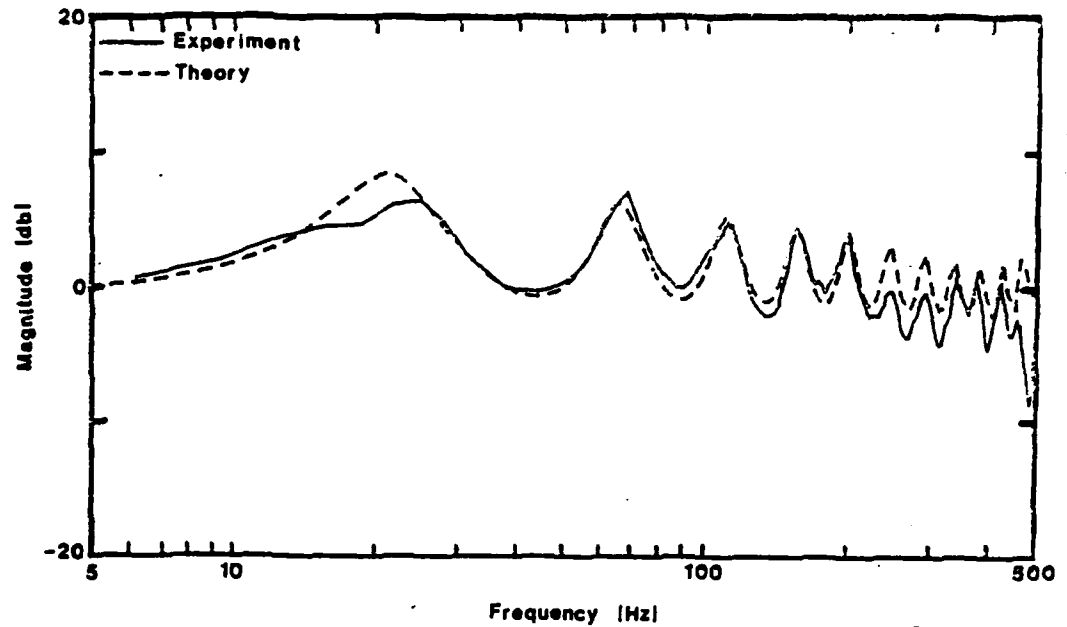
Data Set 21. Line with Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 4.8$  mm; Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



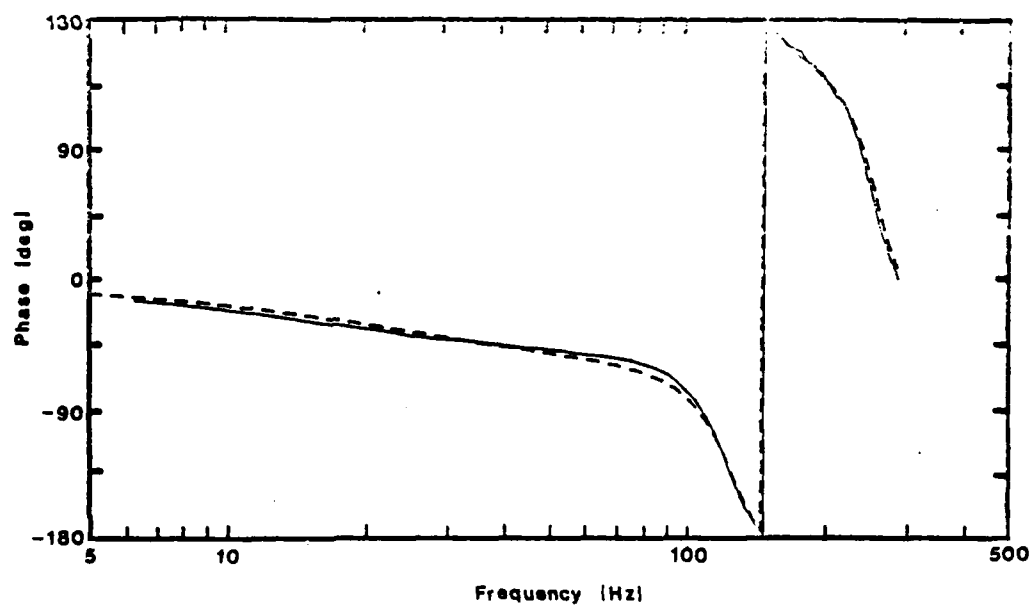
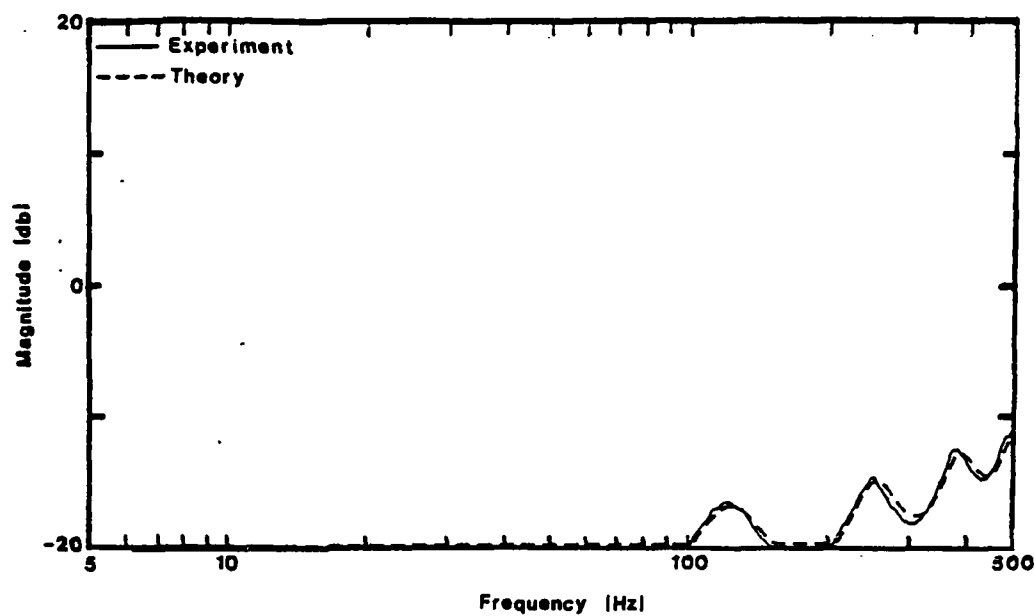
Data Set 22. Line with Load Impedance  
( $\lambda = 4.8$  m,  $d = 7.6$  mm; Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



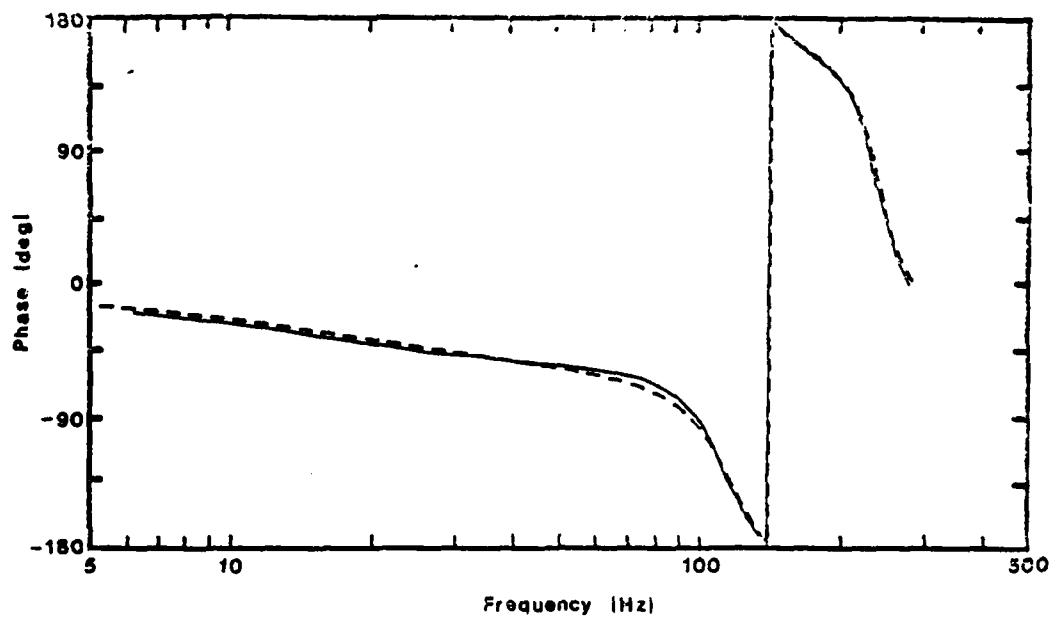
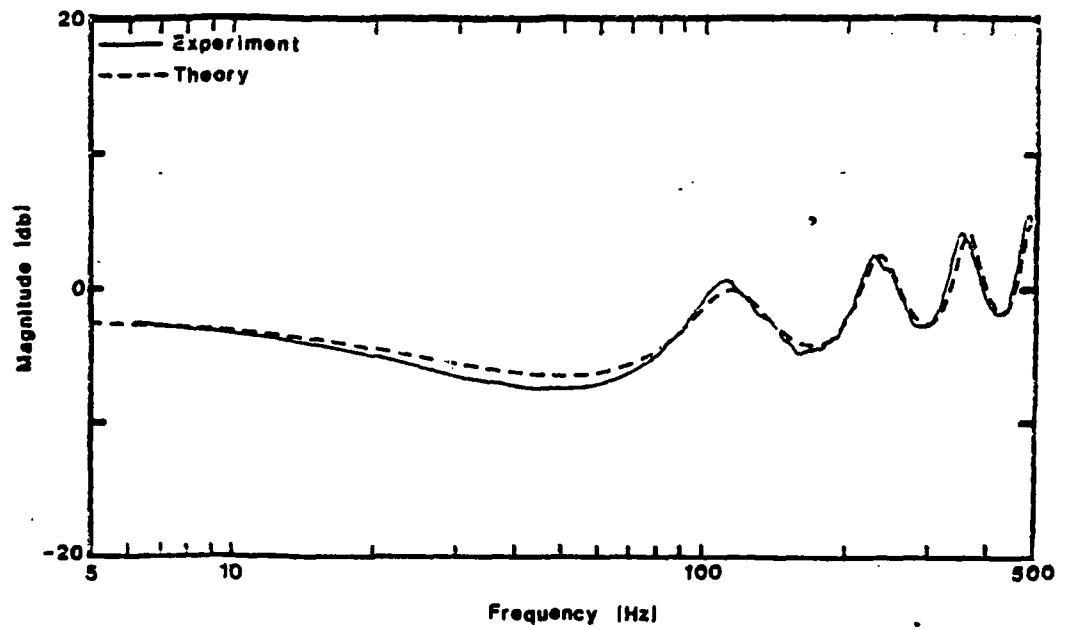
Data Set 23. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



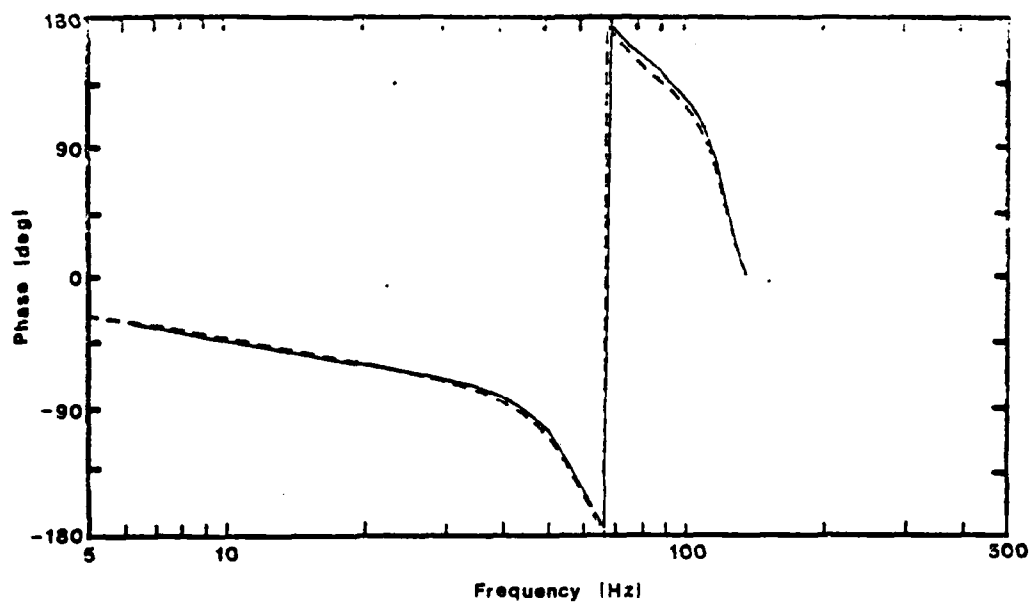
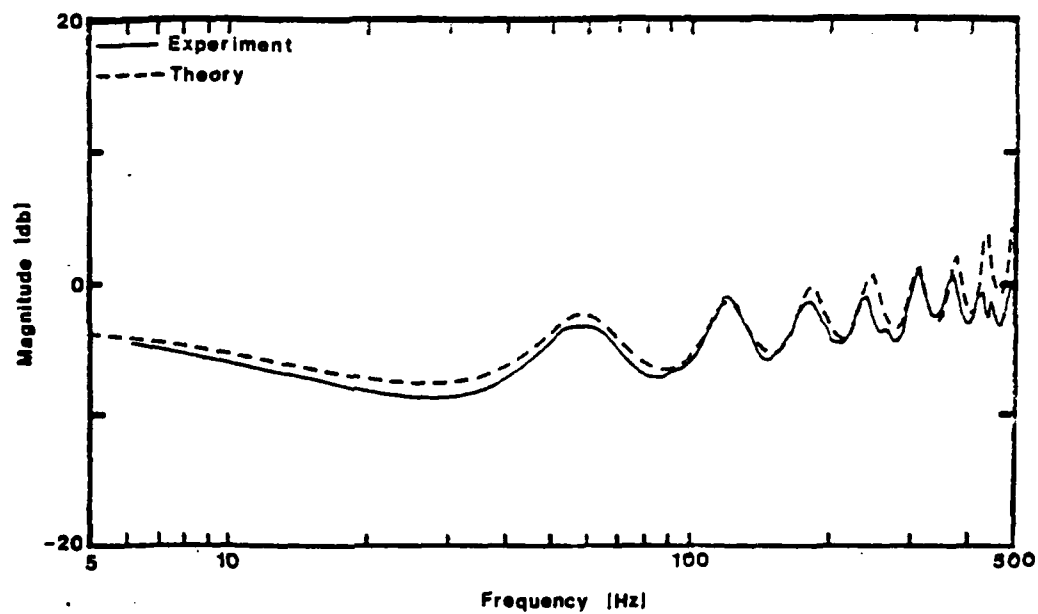
Data Set 24. Line with Load Impedance  
 ( $\ell = 14.8$  m,  $d = 7.6$  mm; Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



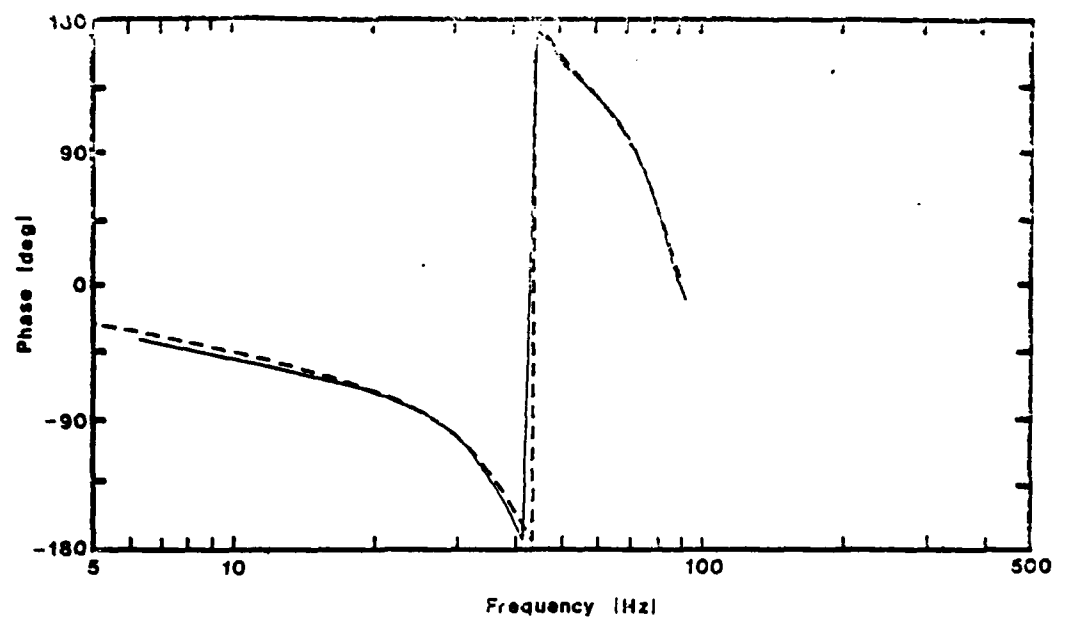
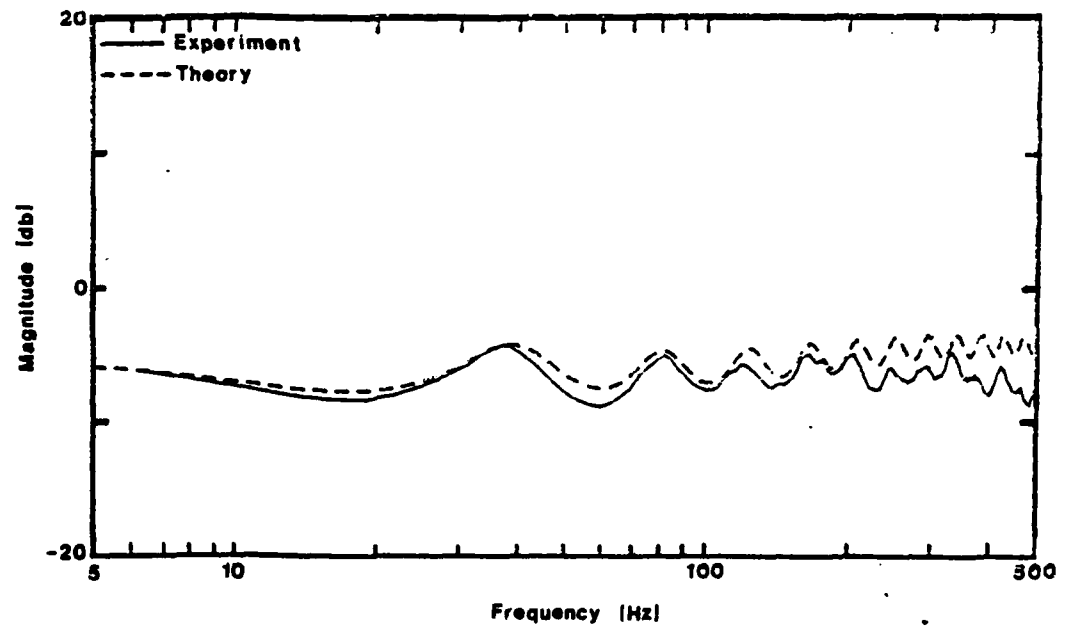
Data Set 25. Line with Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



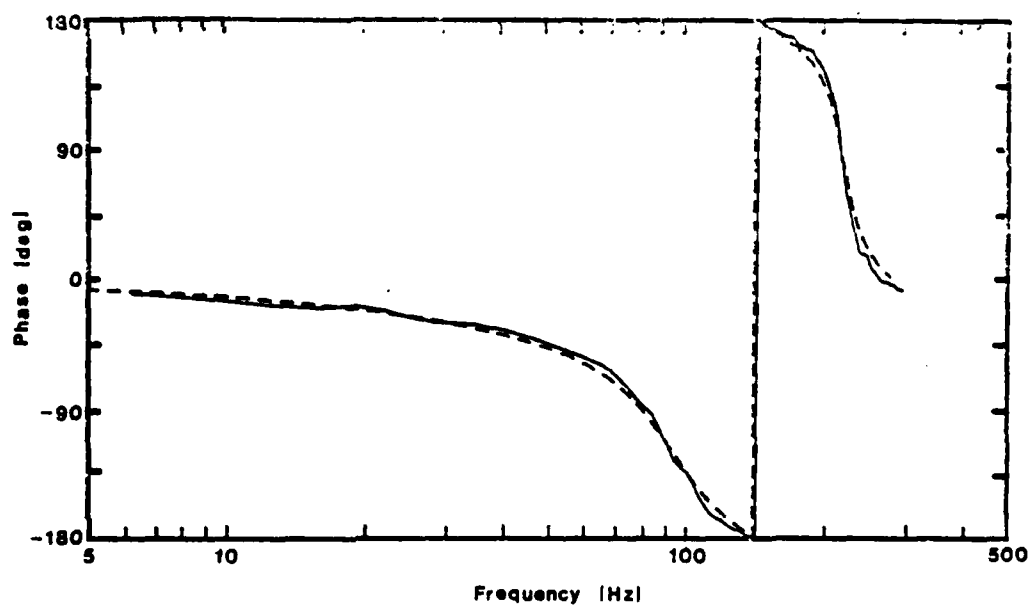
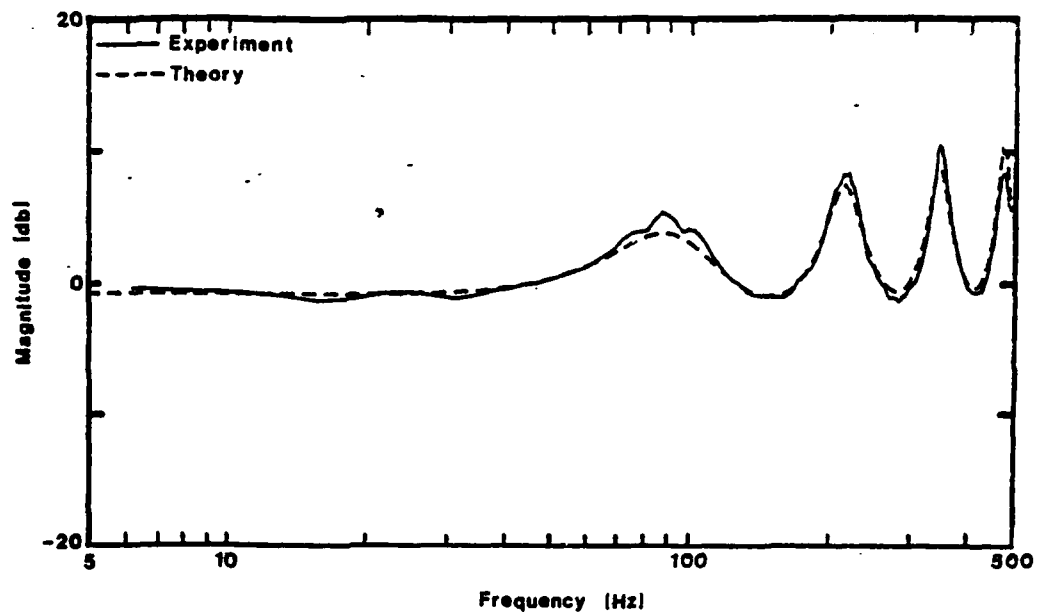
Data Set 26. Line with Load Impedance  
 ( $\ell = 4.8$  m,  $d = 4.8$  mm; Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



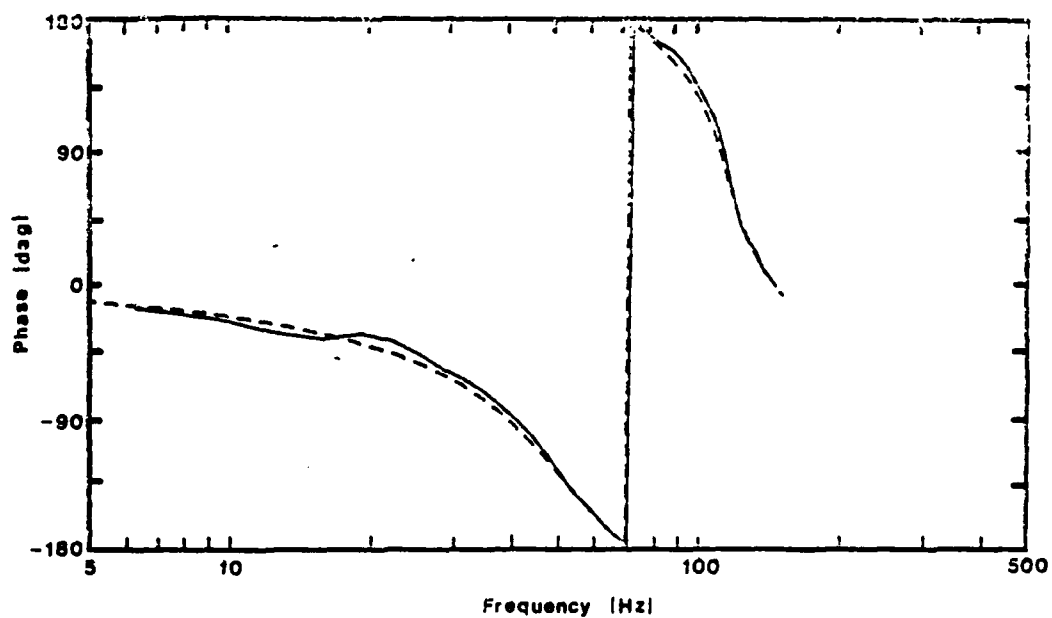
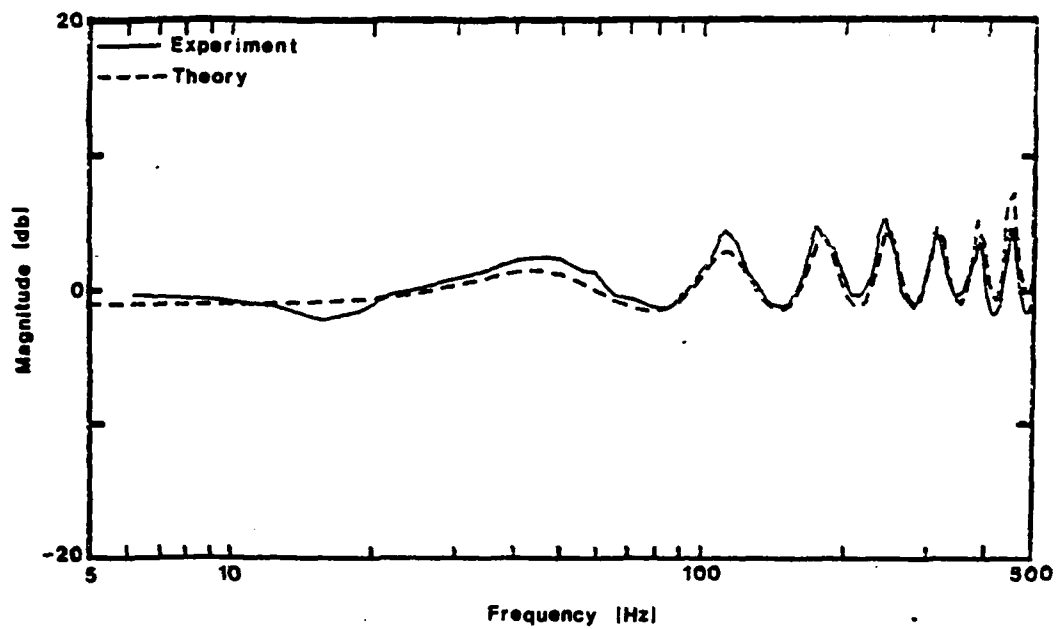
Data Set 27. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 4.8$  mm; Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



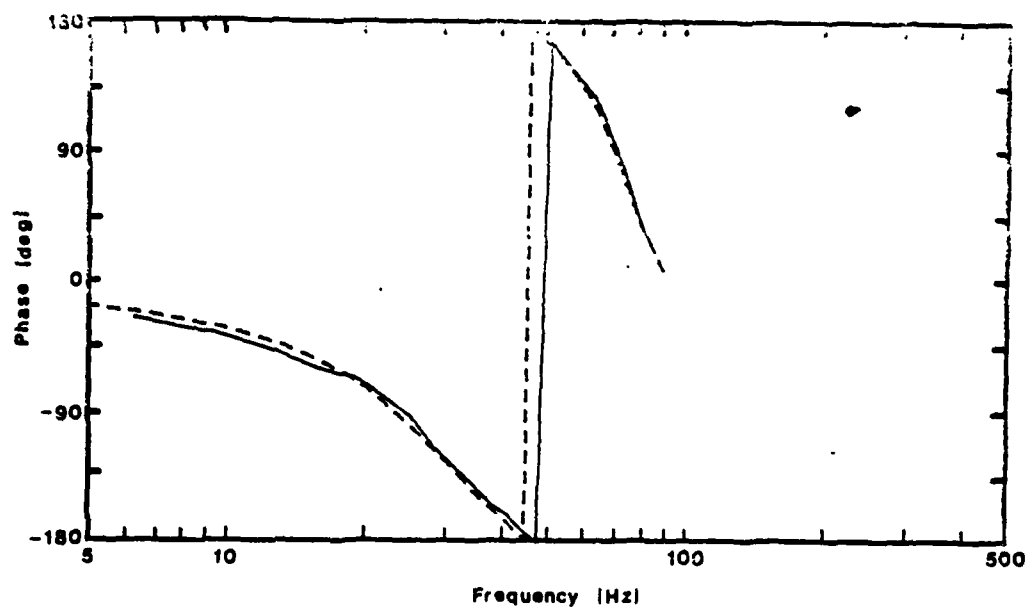
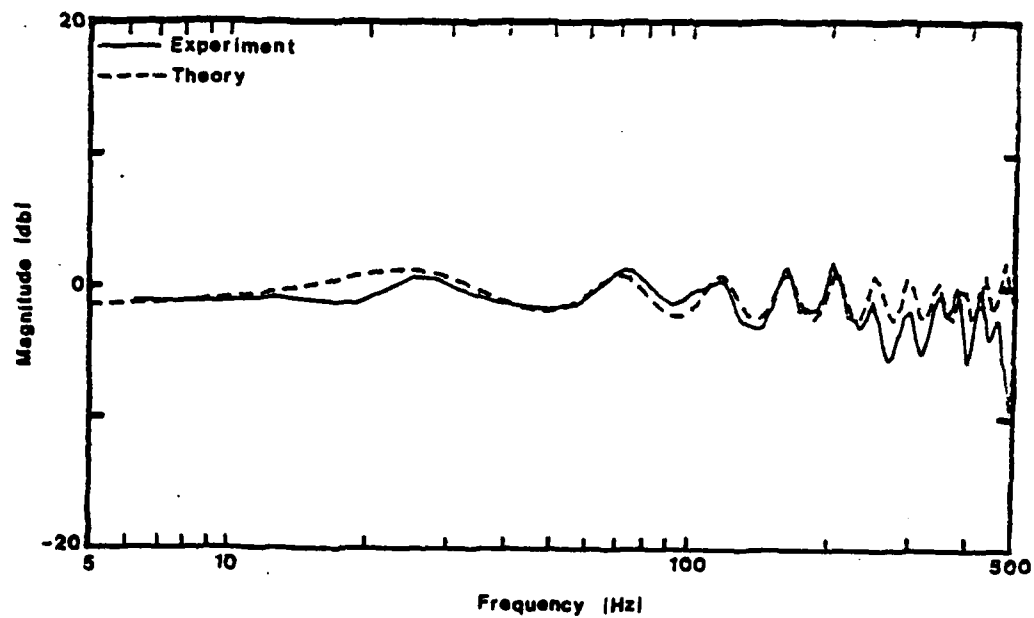
Data Set 28. Line with Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



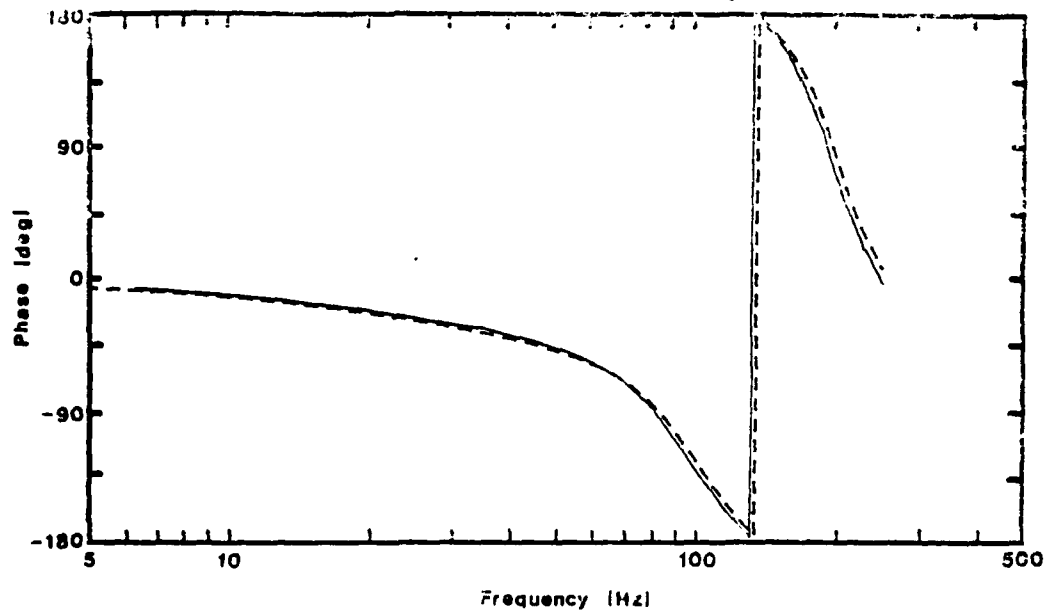
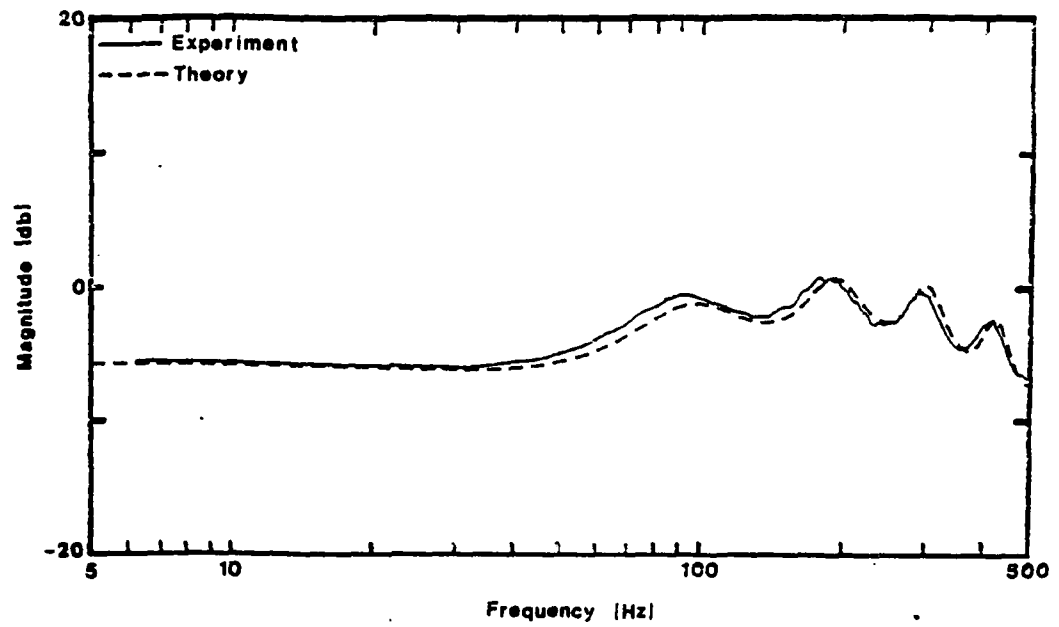
Data Set 29. Line with Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 7.6$  mm; Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



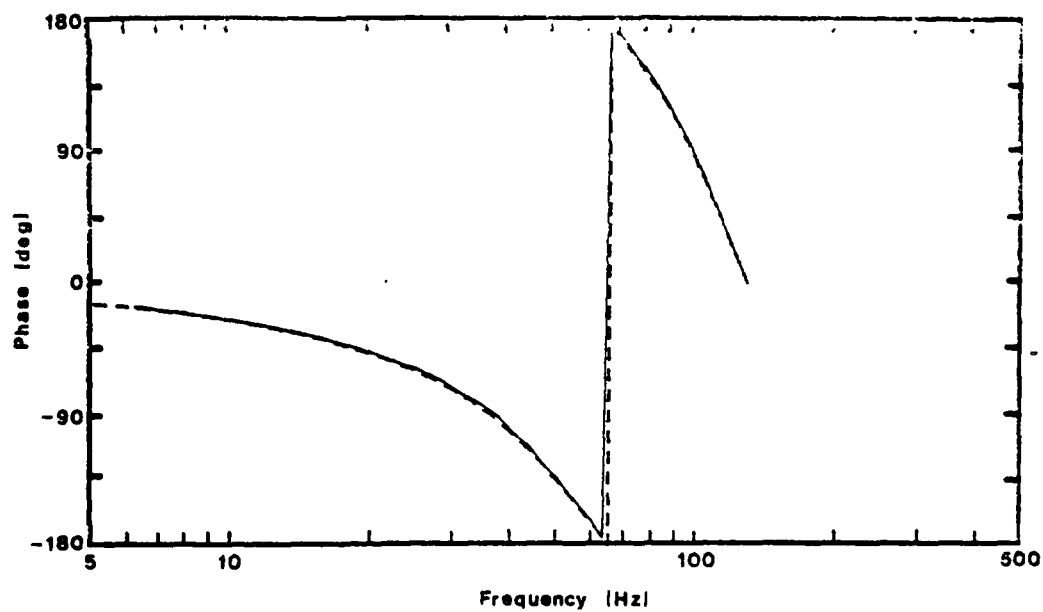
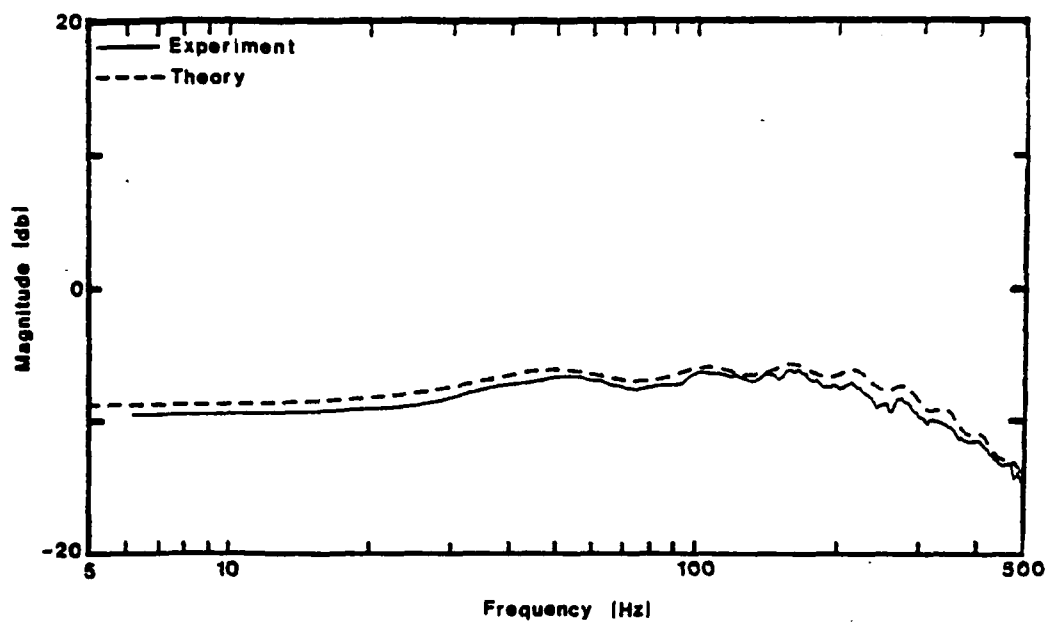
Data Set 30. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



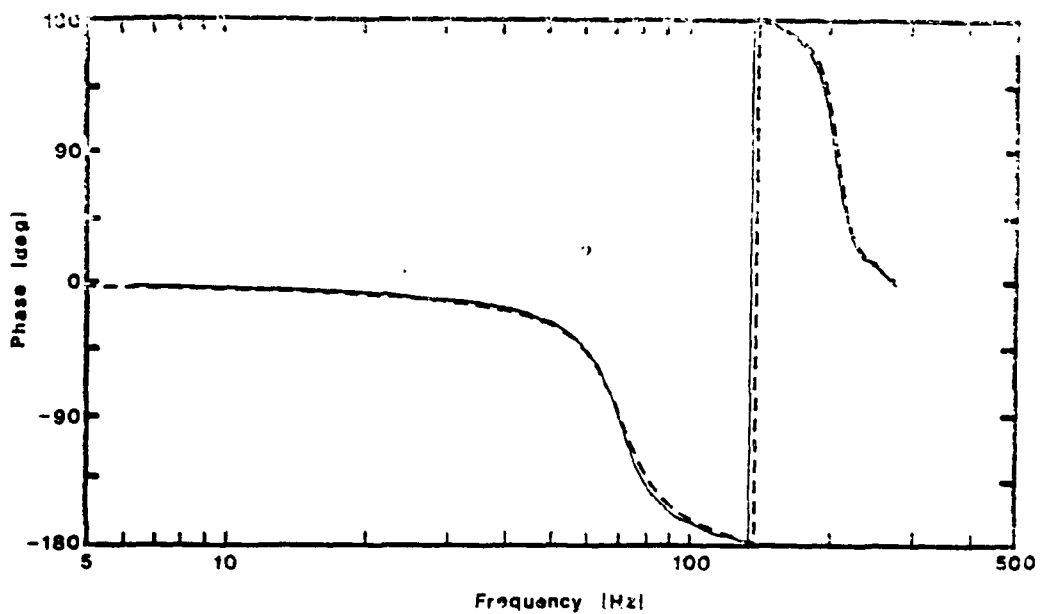
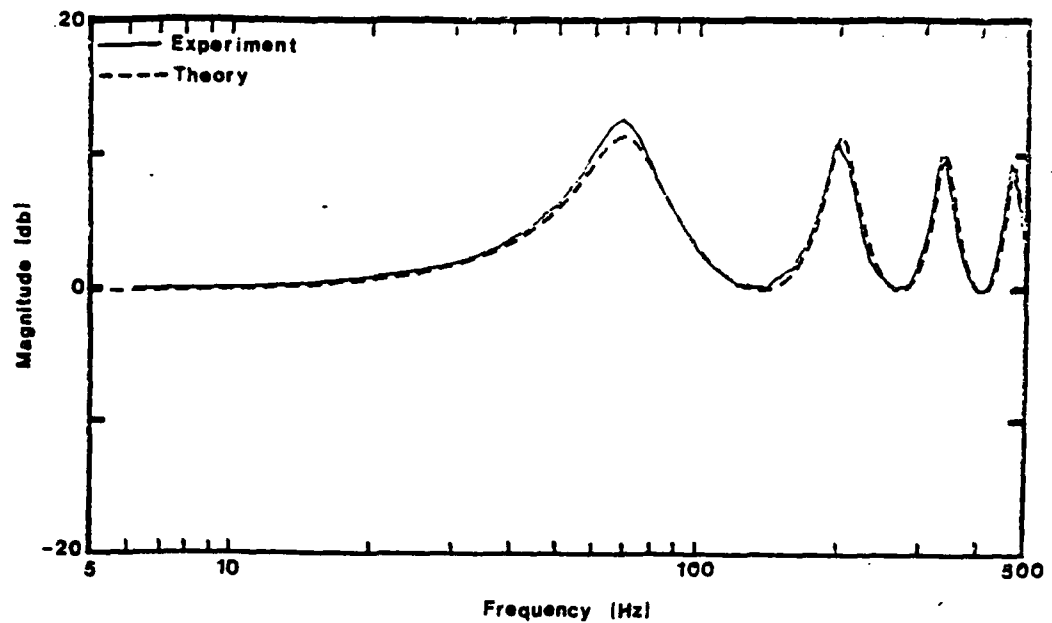
Data Set 31. Line with Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



Data Set 32. Line with Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



Data Set 33. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 1.7$  mm; Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



Data Set 34. Line with Load Impedance  
 ( $\ell = 4.8$  m,  $d = 4.8$  mm; Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)

AD-A134 484

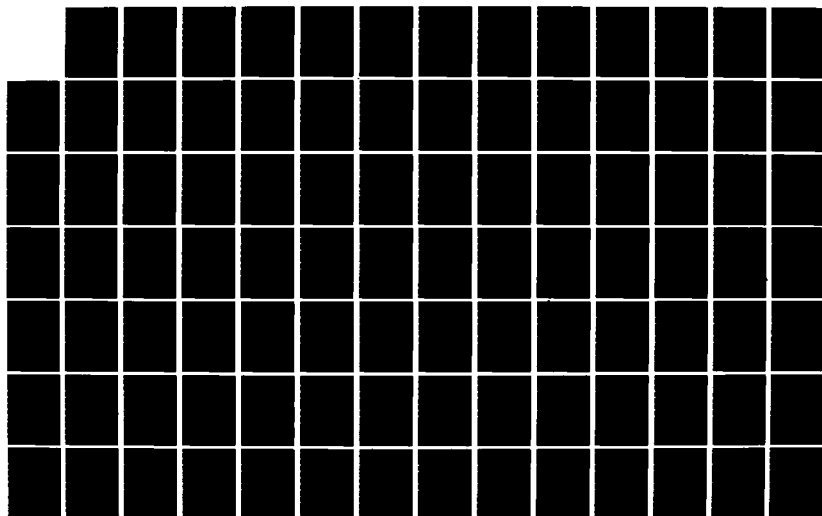
FREQUENCY RESPONSE OF HYDRAULIC TRANSMISSION LINES(U)  
TEXAS UNIV AT ARLINGTON FLUID CONTROLS CENTER FOR  
RESEARCH AND DEVELOPMENT R L WOODS ET AL. 25 MAY 82  
NADC-80252-60 N62669-81-M-3056

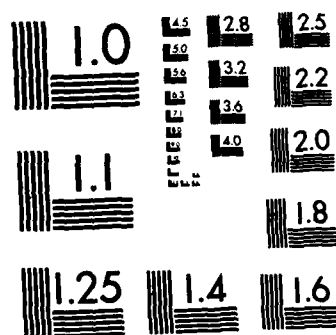
2/3

UNCLASSIFIED

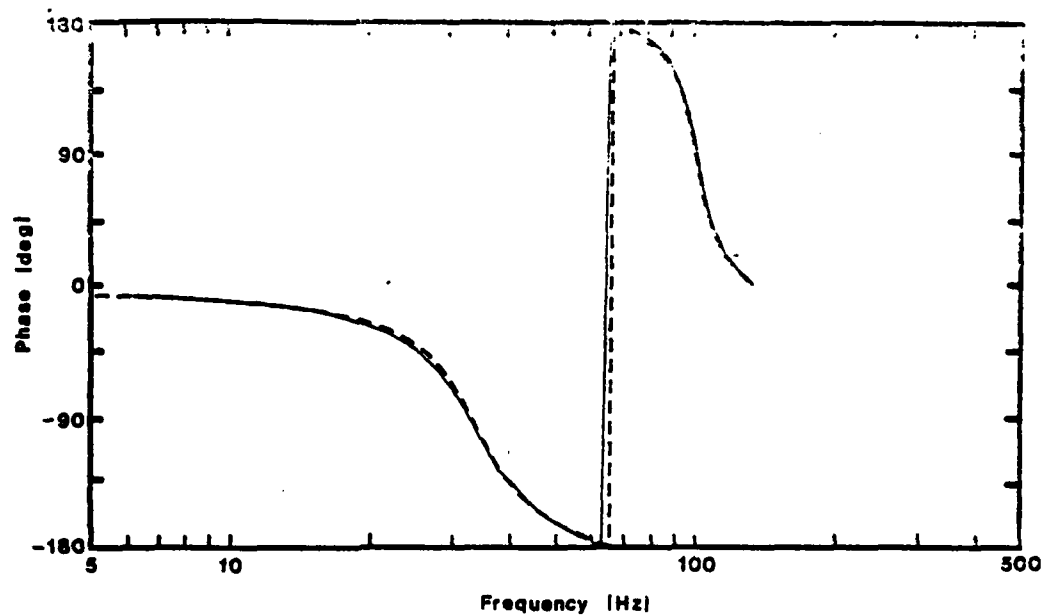
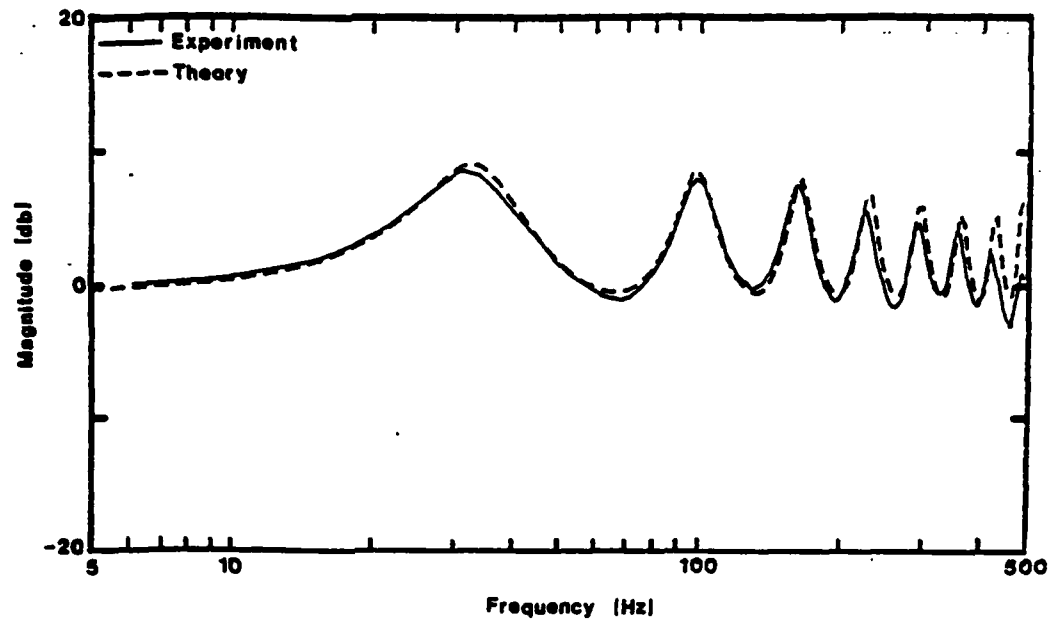
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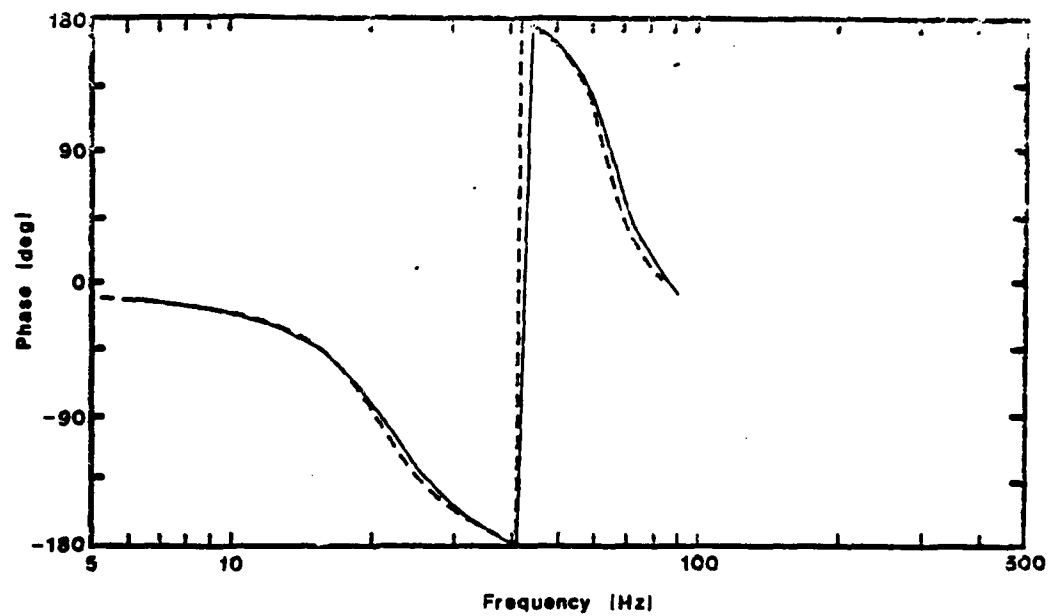
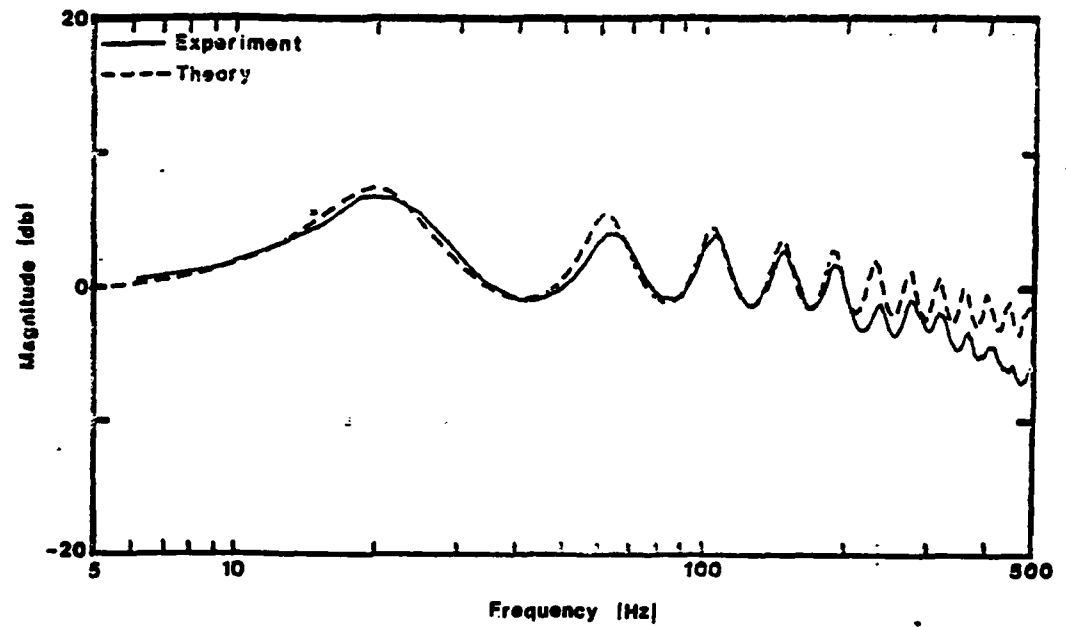




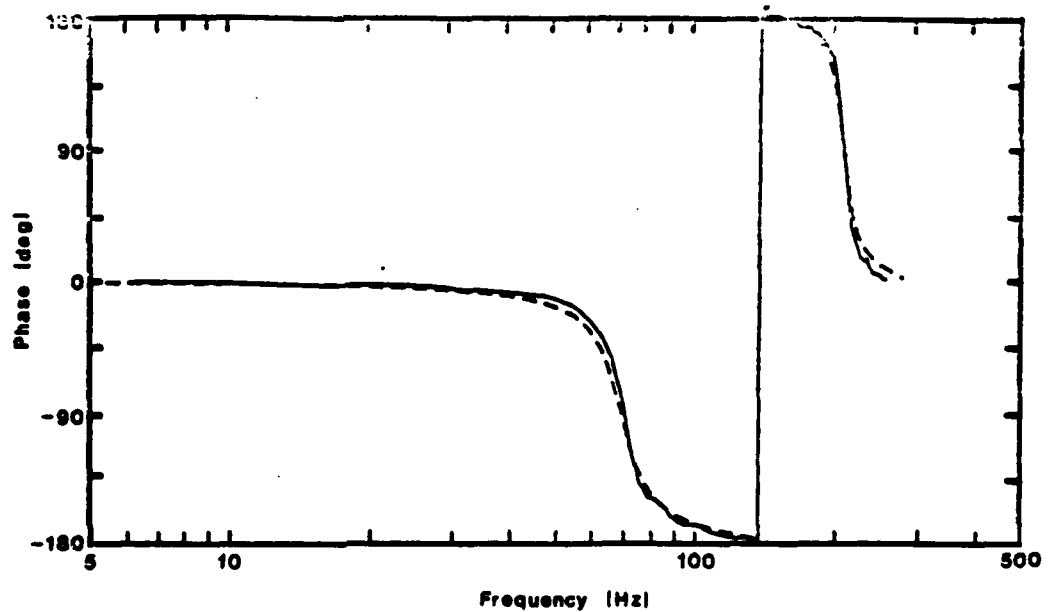
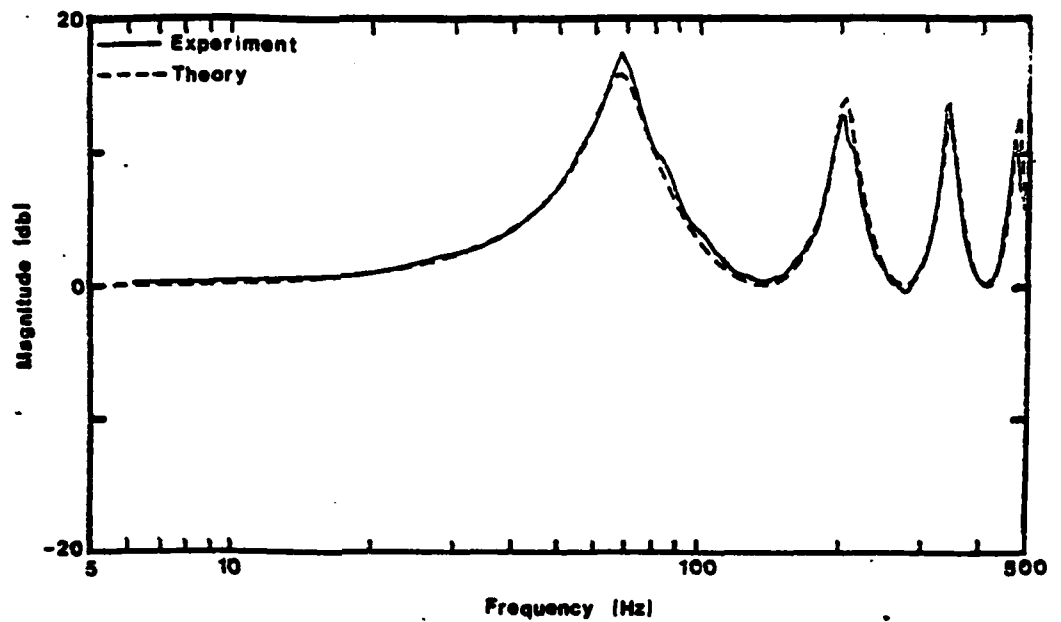
MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A



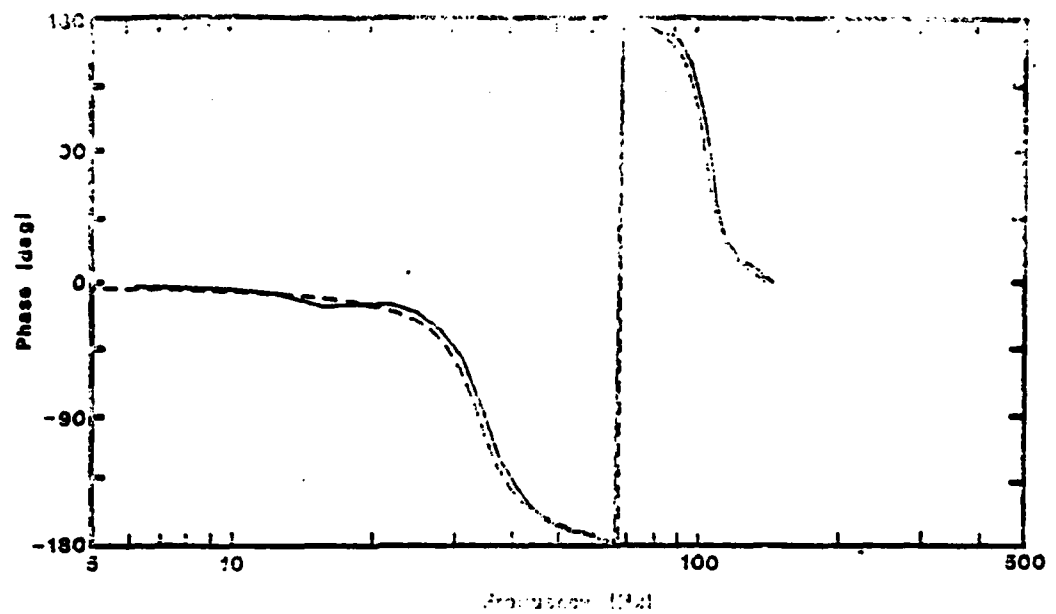
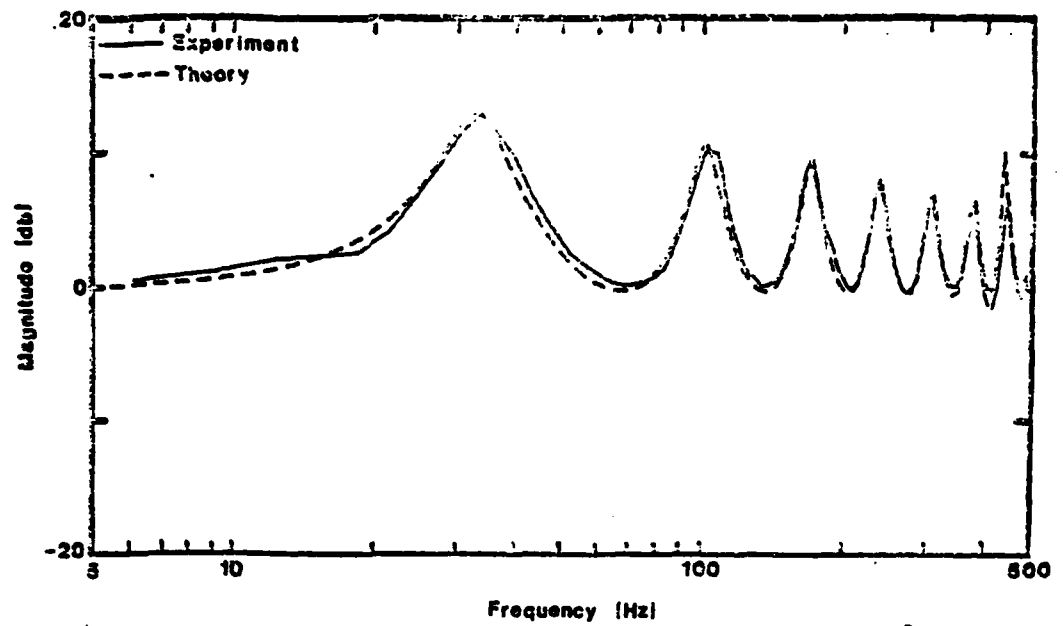
Data Set 35. Line with Load Impedance  
 ( $l = 9.6$  m,  $d = 4.8$  mm; Resistor #6,  $l = 297$  mm,  $d = .88$  mm)



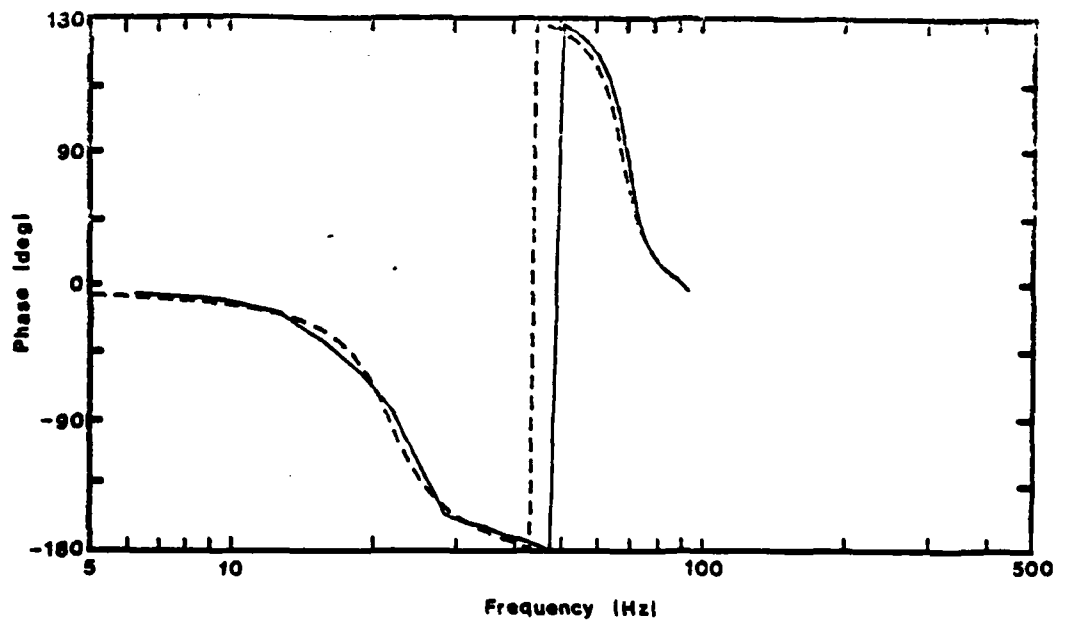
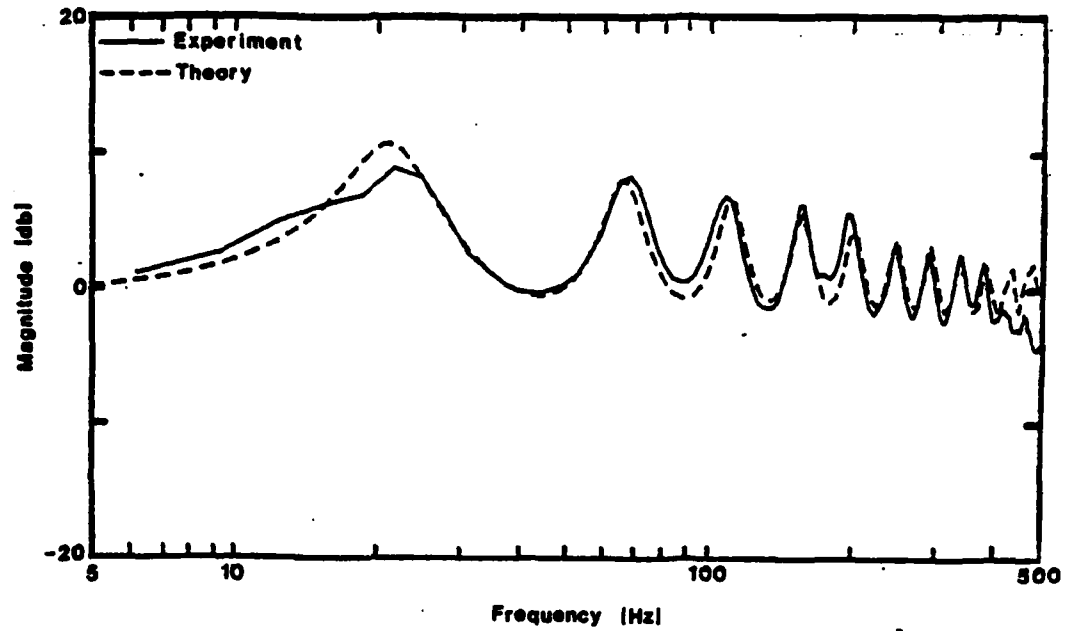
Data Set 36. Line with Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 4.8$  mm; Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



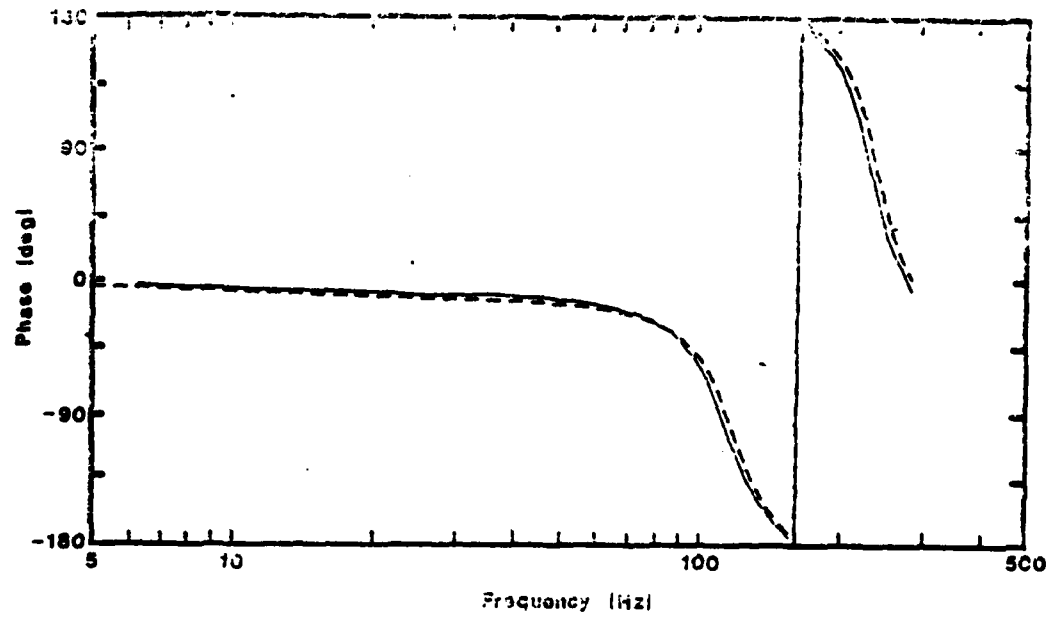
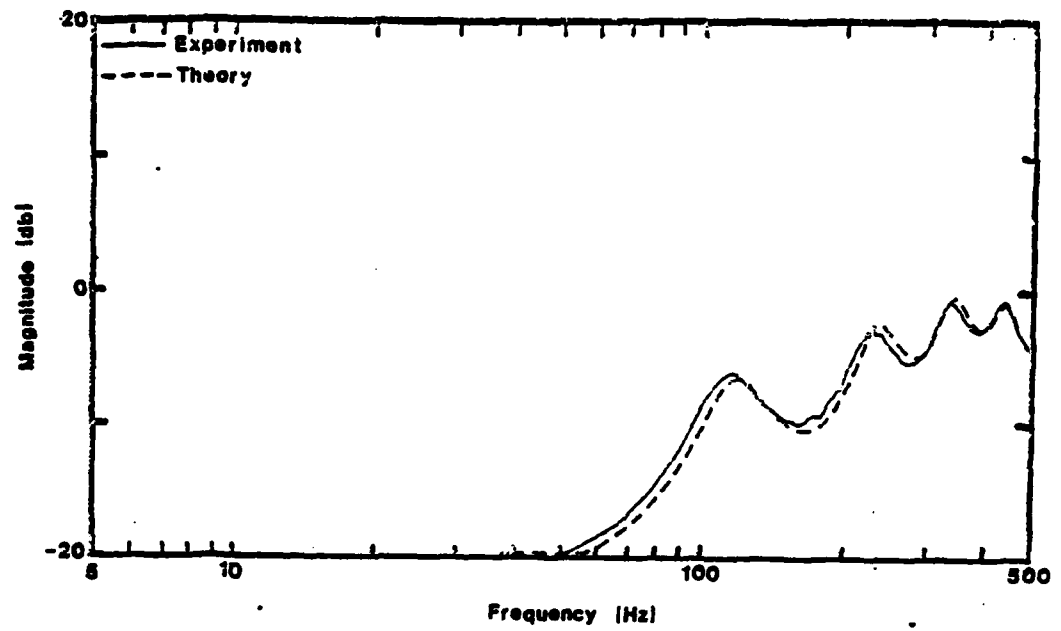
Data Set 37. Line with Load Impedance  
 ( $l = 4.8$  m,  $d = 7.6$  mm; Resistor #6,  $l = 297$  mm,  $d = .88$  mm)



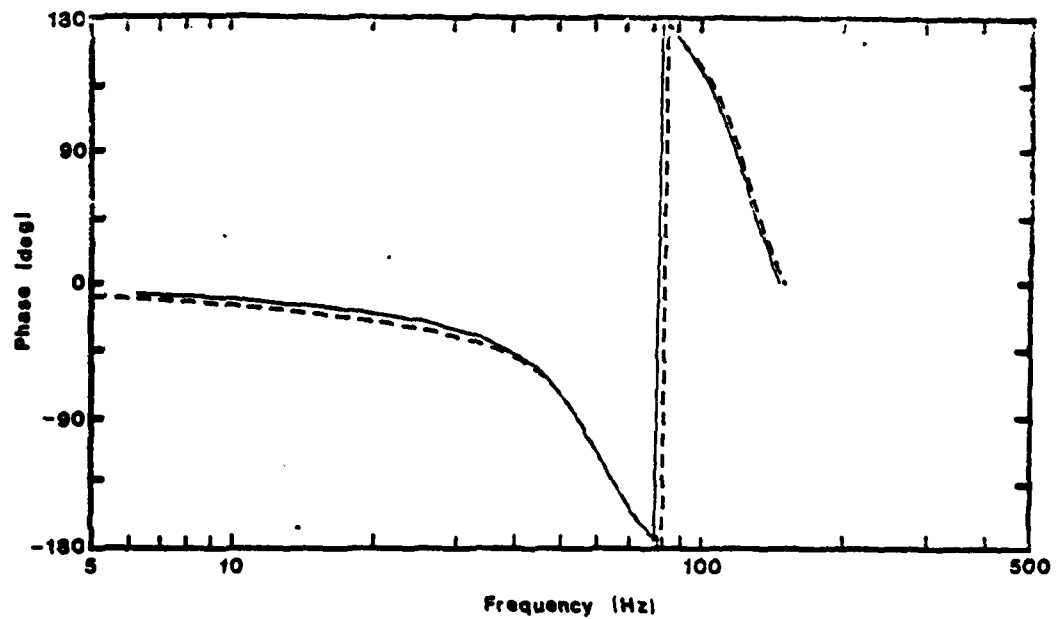
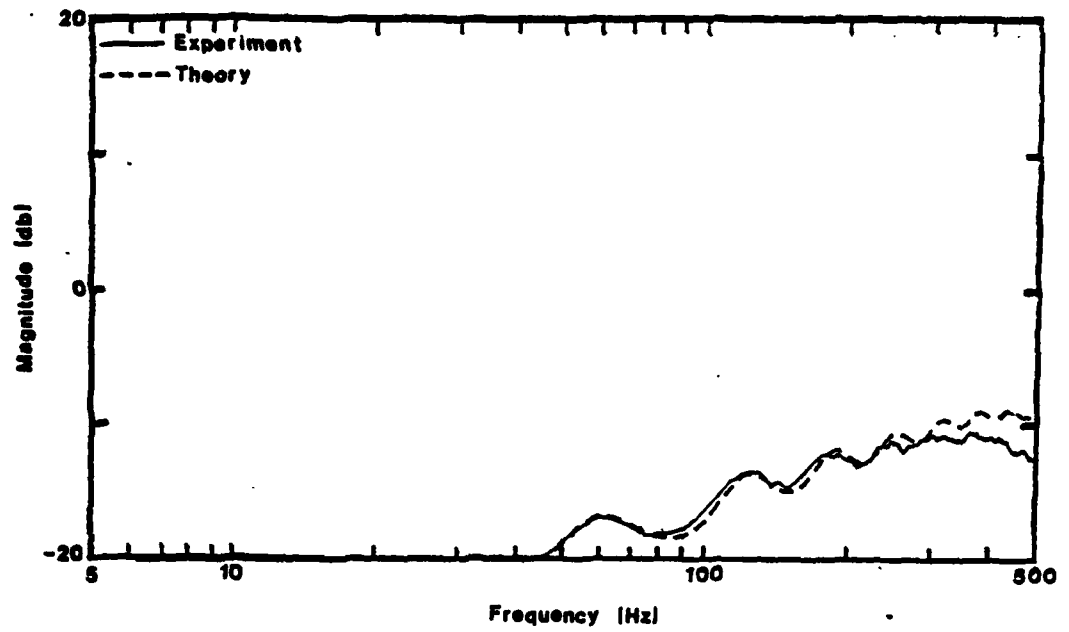
Data Set 39. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



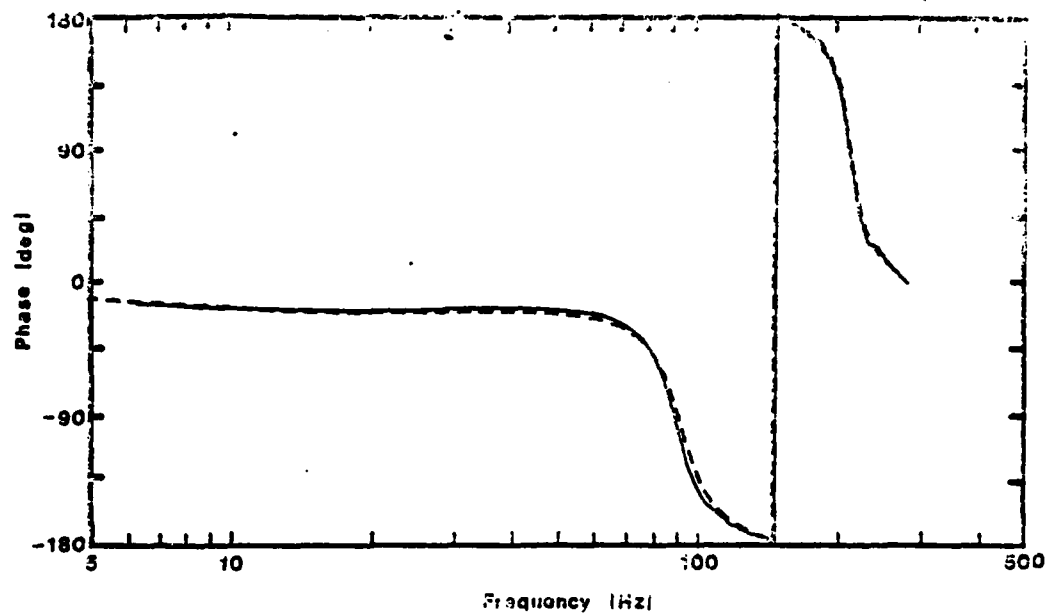
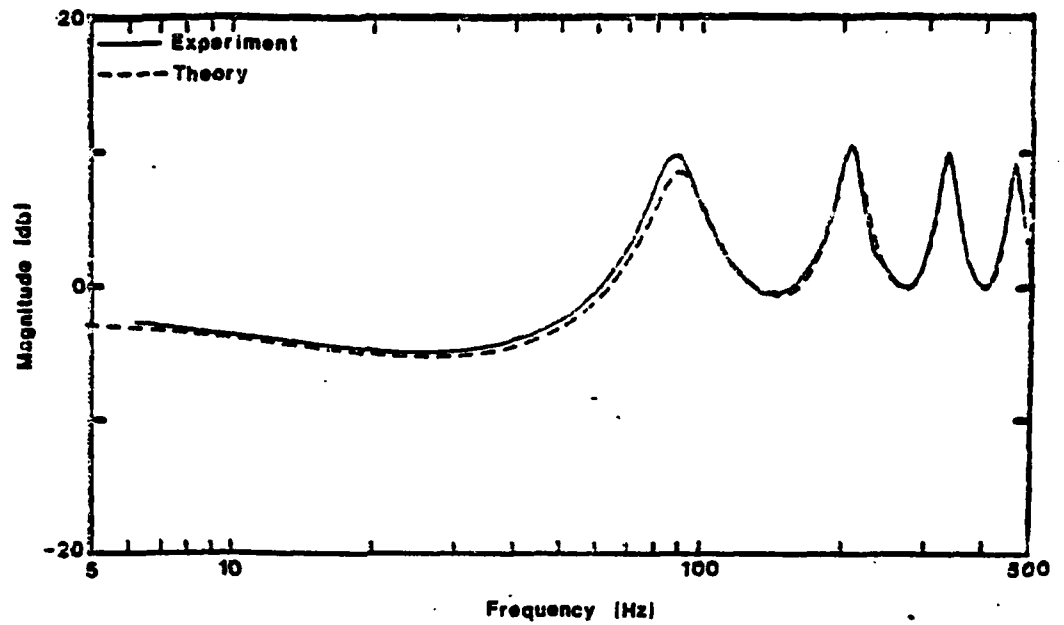
Data Set 39. Line with Load Impedance  
 ( $\ell = 14.8$  m,  $d = 7.6$  mm; Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



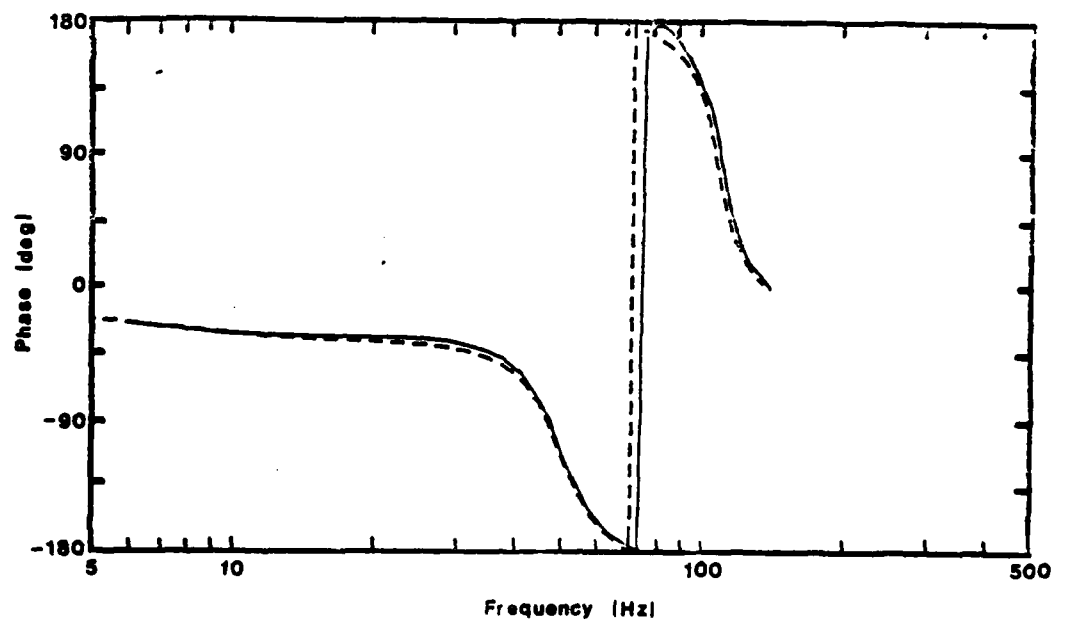
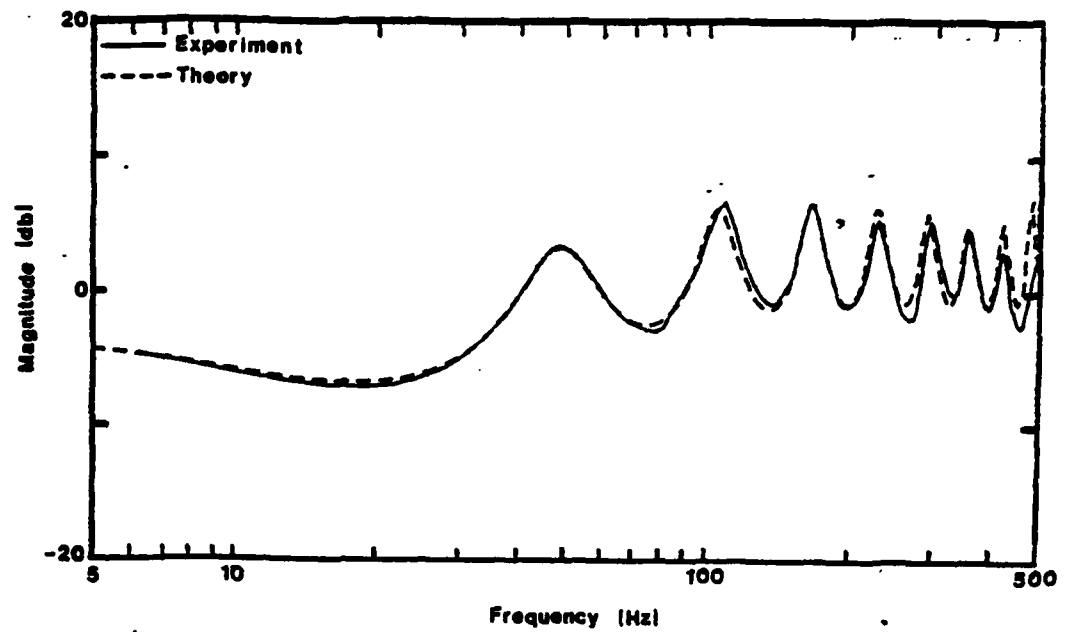
Data Set 40. Line with Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Resistor #7,  $\lambda = 290$  mm,  $d = 1.63$  mm)



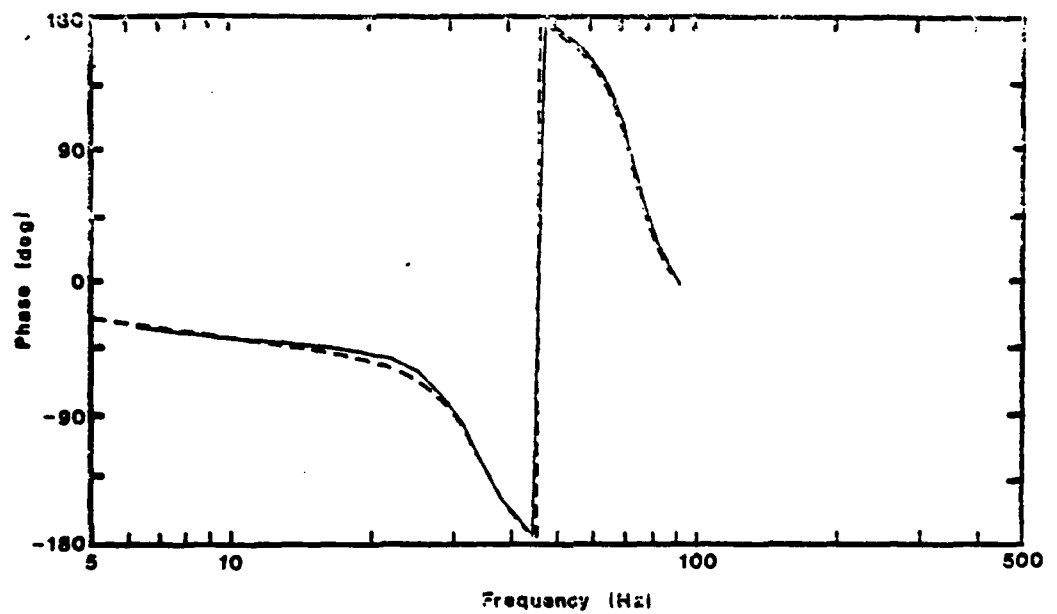
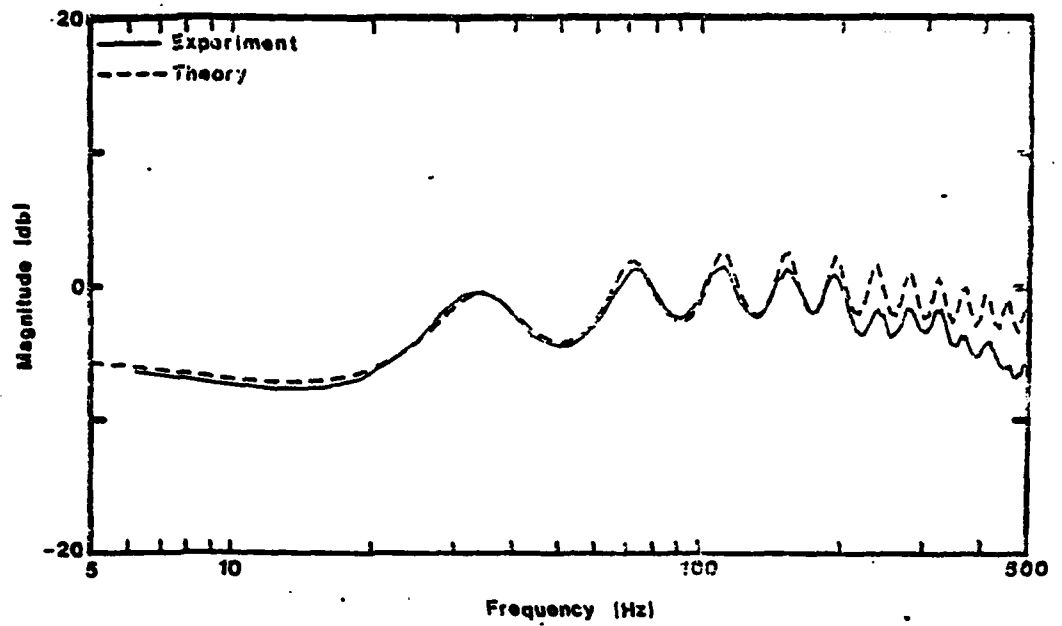
Data Set 41. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



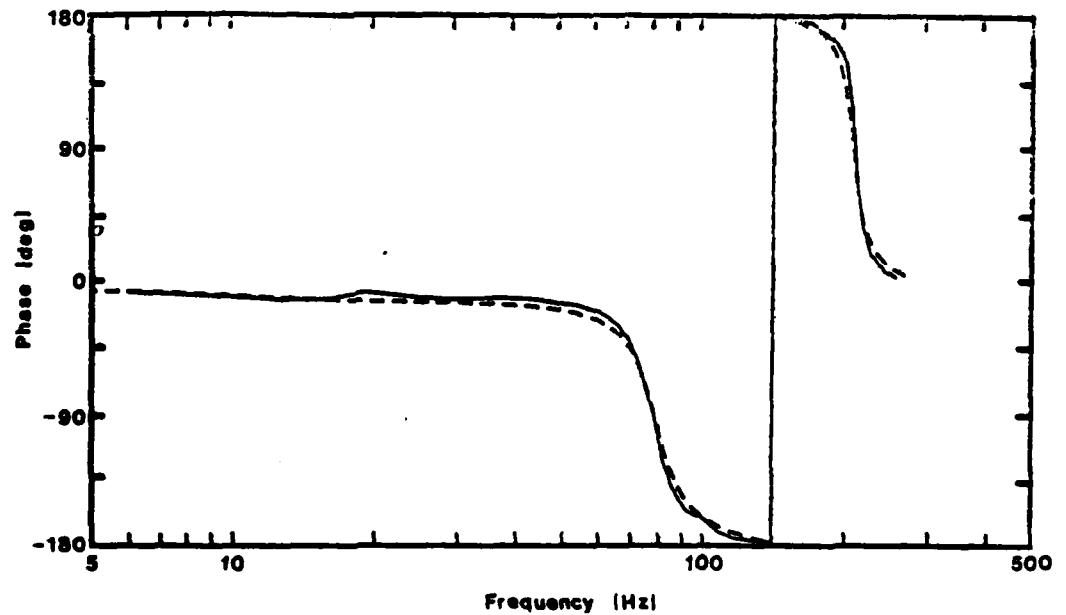
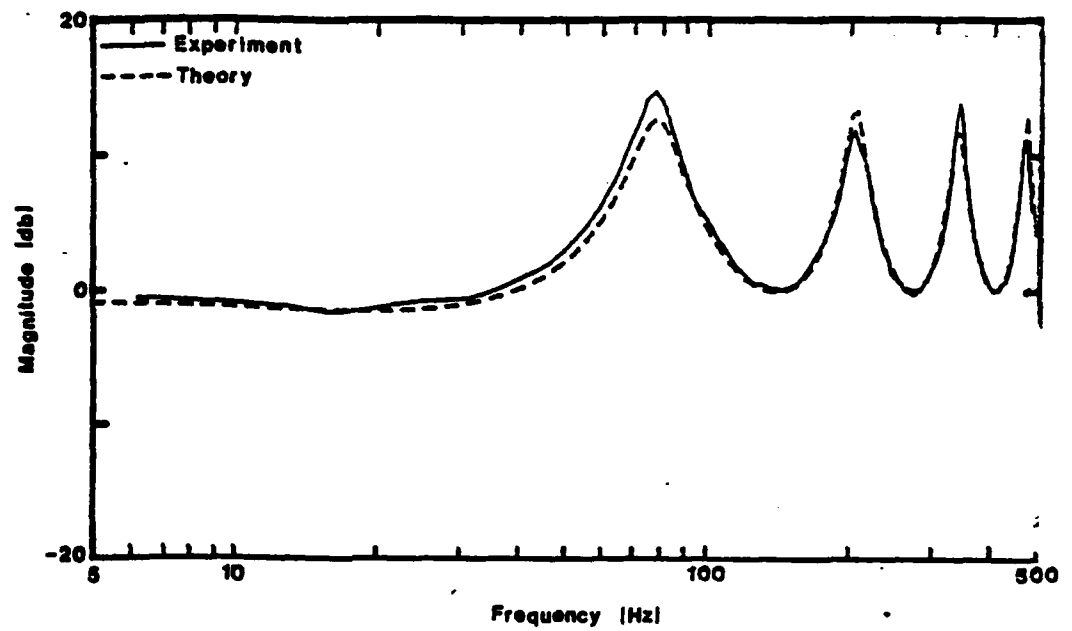
Data Set 42. Line with Load Impedance  
 $(\lambda = 4.8 \text{ m}, d = 4.8 \text{ mm}; \text{Resistor \#7}, \ell = 290 \text{ mm}, d = 1.63 \text{ mm})$



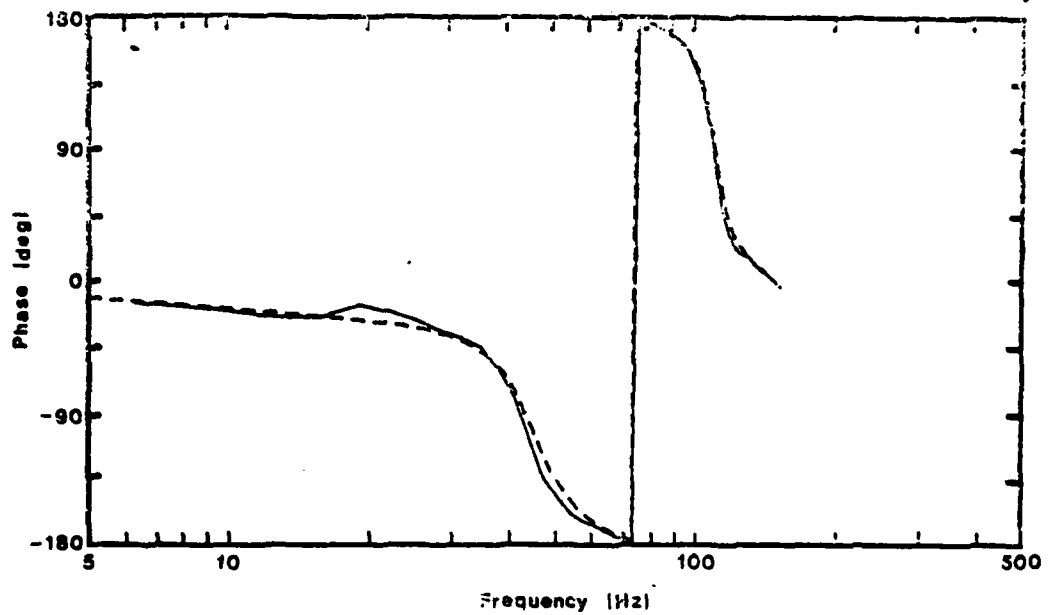
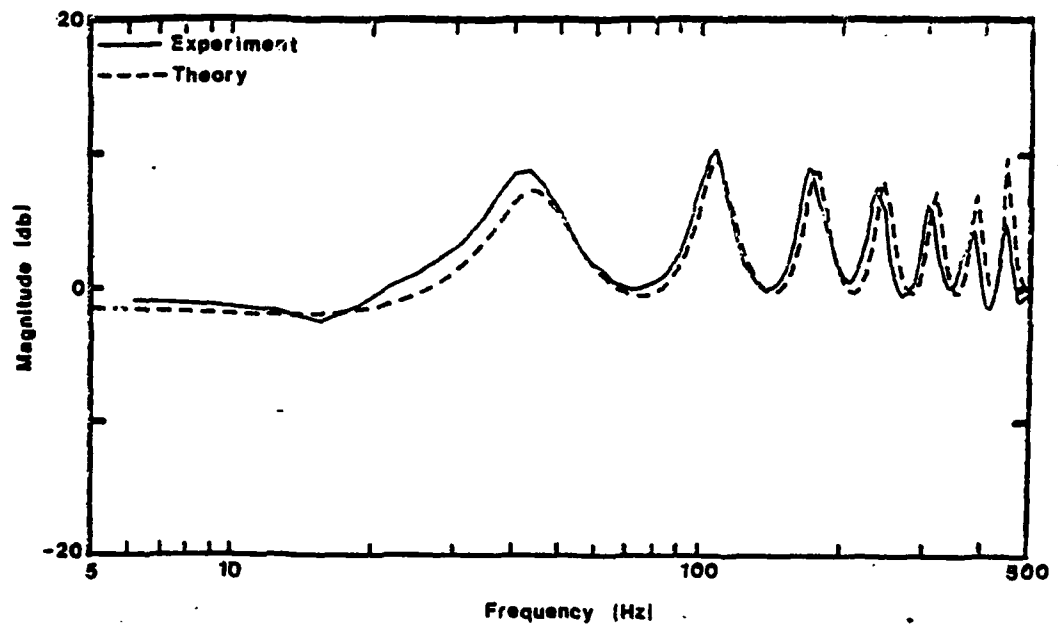
Data Set 43. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Resistor #7.  $\ell = 290$  mm,  $d = 1.63$  mm)



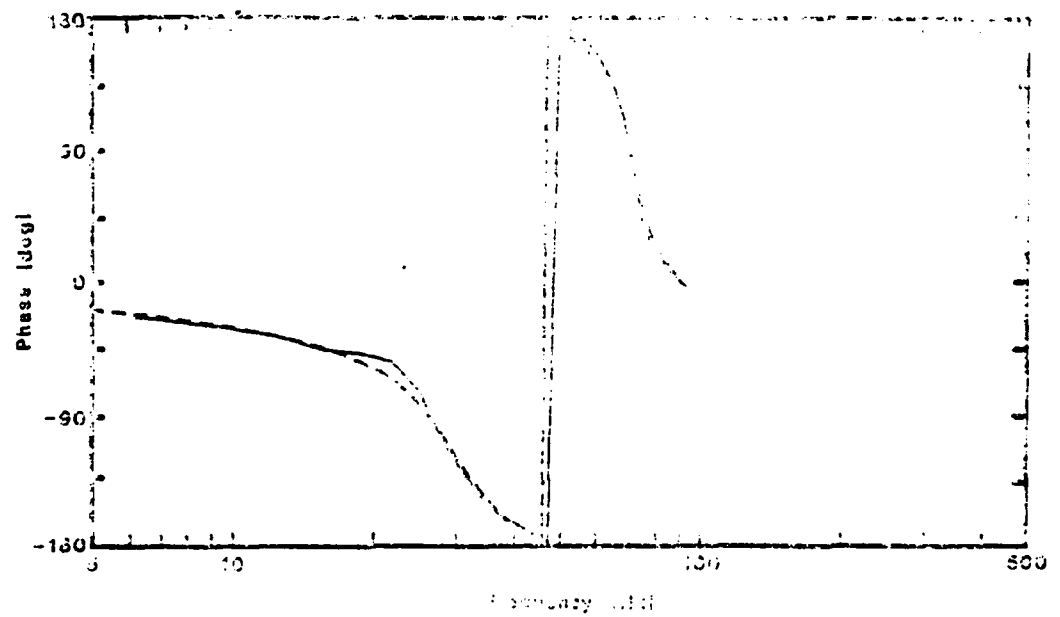
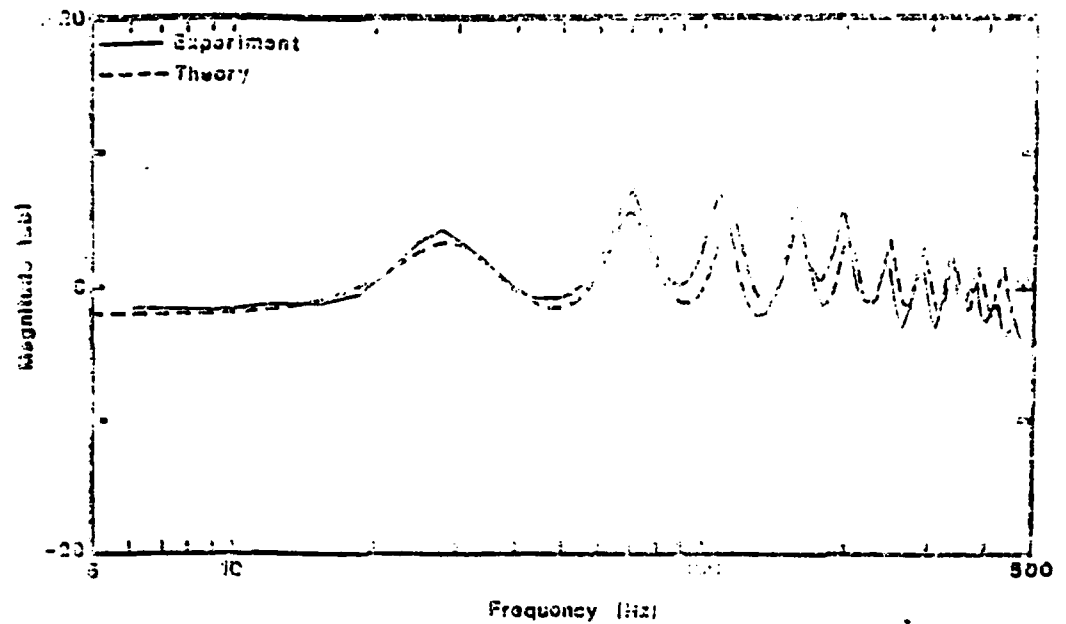
Data Set 44. Line with Load Impedance  
 ( $l = 14.8$  m,  $d = 4.8$  mm; Resistor #7,  $l = 290$  mm,  $d = 1.63$  mm)



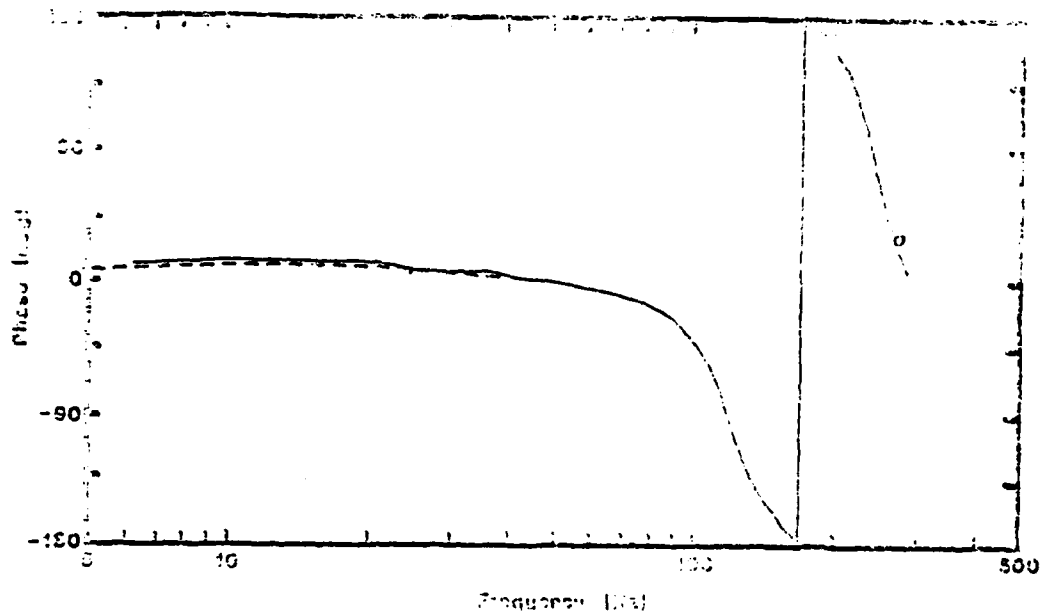
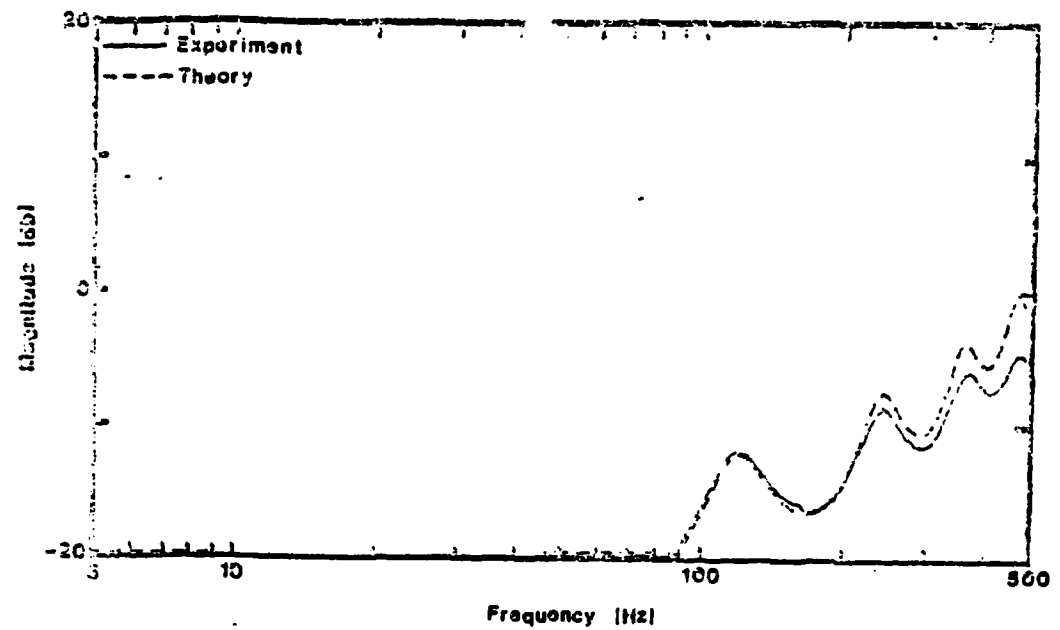
Data Set 45. Line with Load Impedance  
 ( $l = 4.8$  m,  $d = 7.6$  mm; Resistor #7,  $l = 290$  mm,  $d = 1.63$  mm)



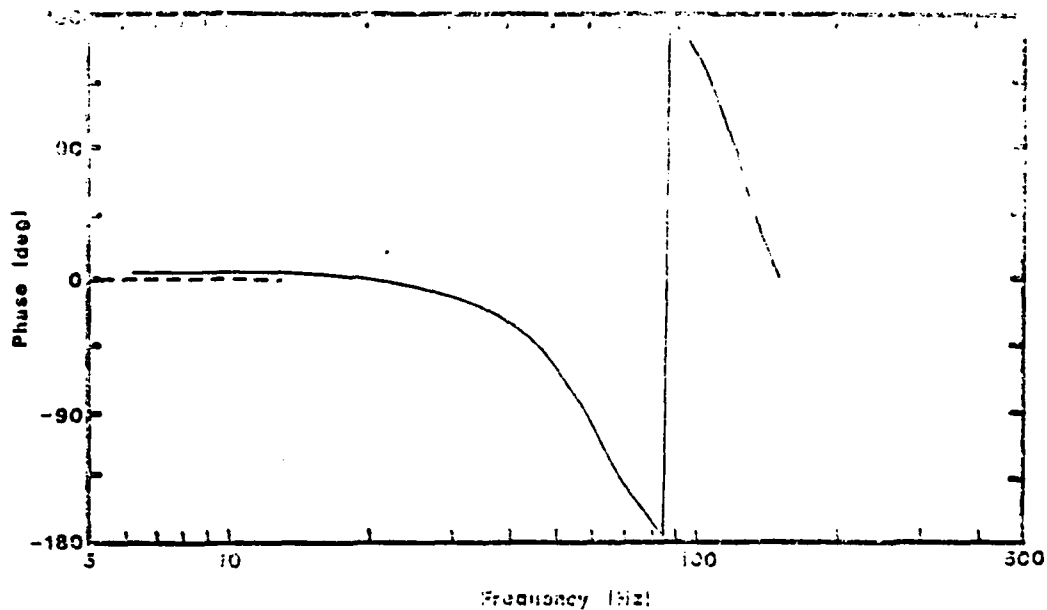
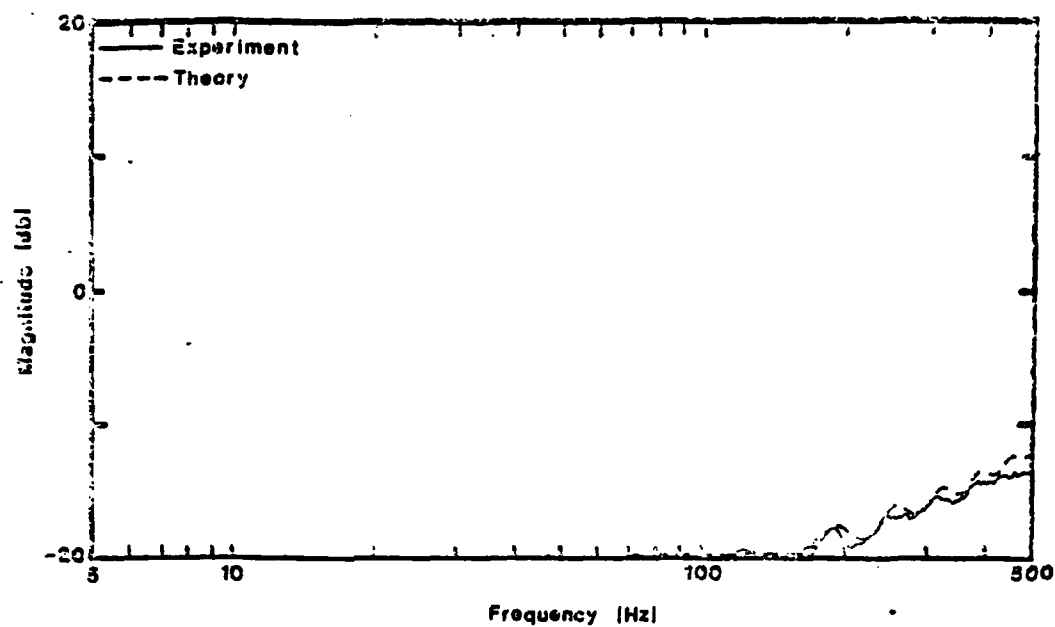
Data Set 46. Line with Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



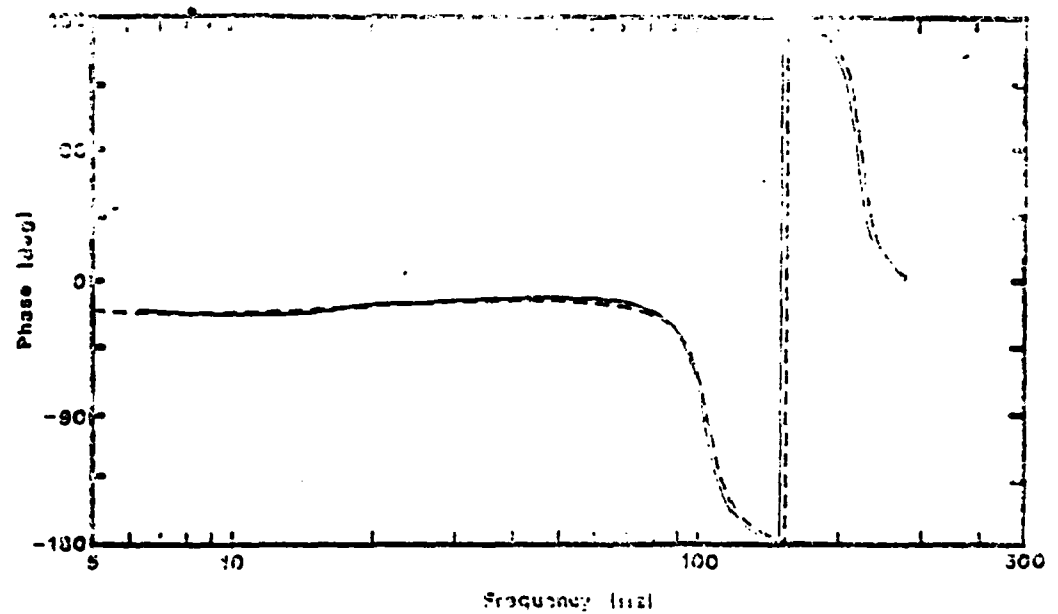
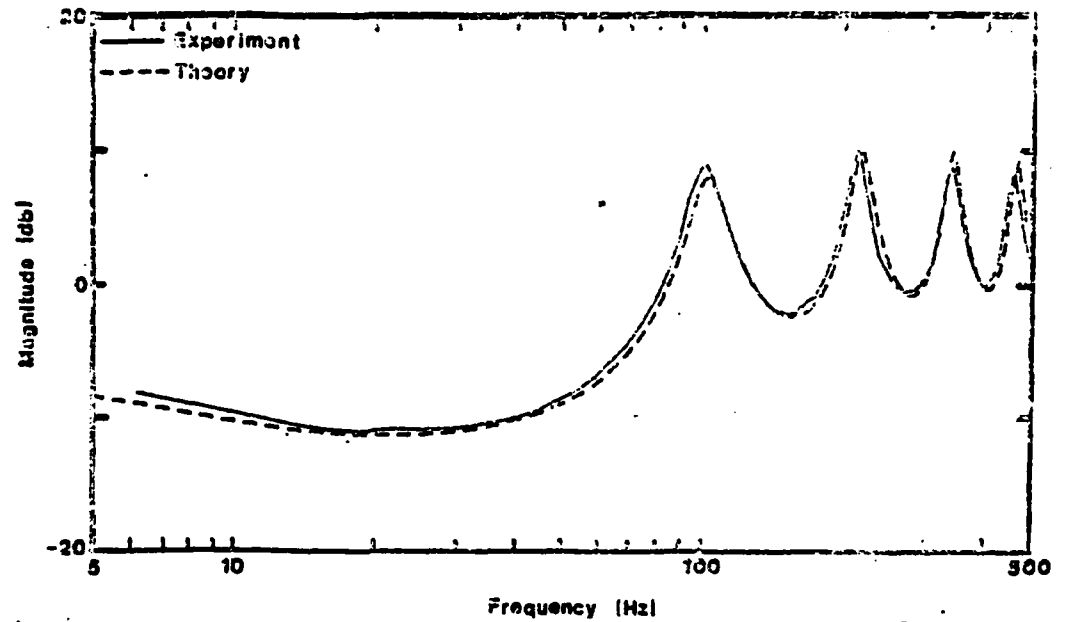
Data Set 47. Line with Load Impedance  
 $(\lambda = 14.3 \text{ m}, d = 7.5 \text{ mm}; \text{Resistor \#7}, \lambda = 290 \text{ mm}, d = 1.53 \text{ mm})$



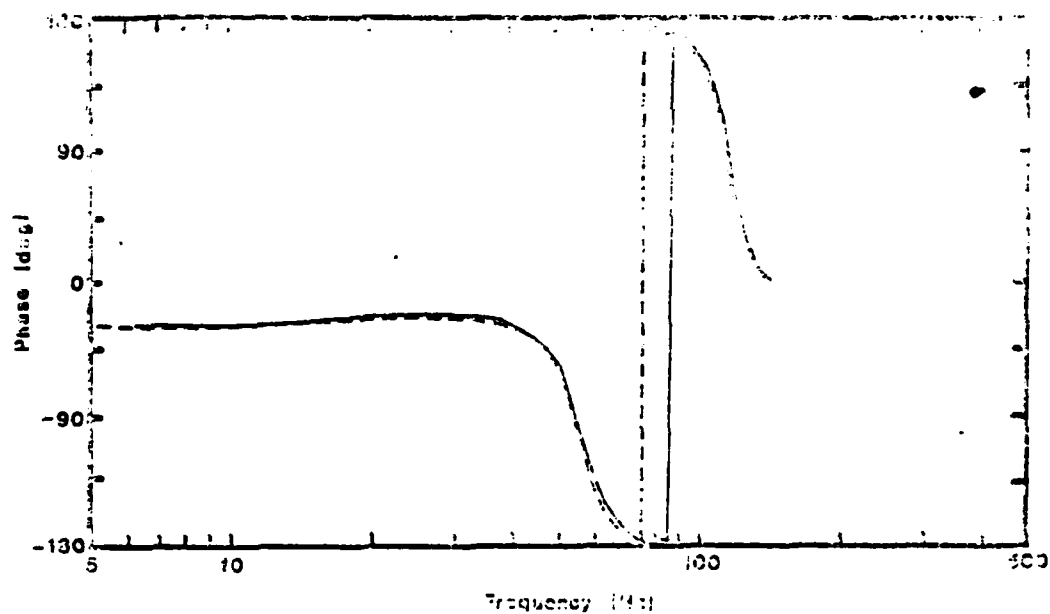
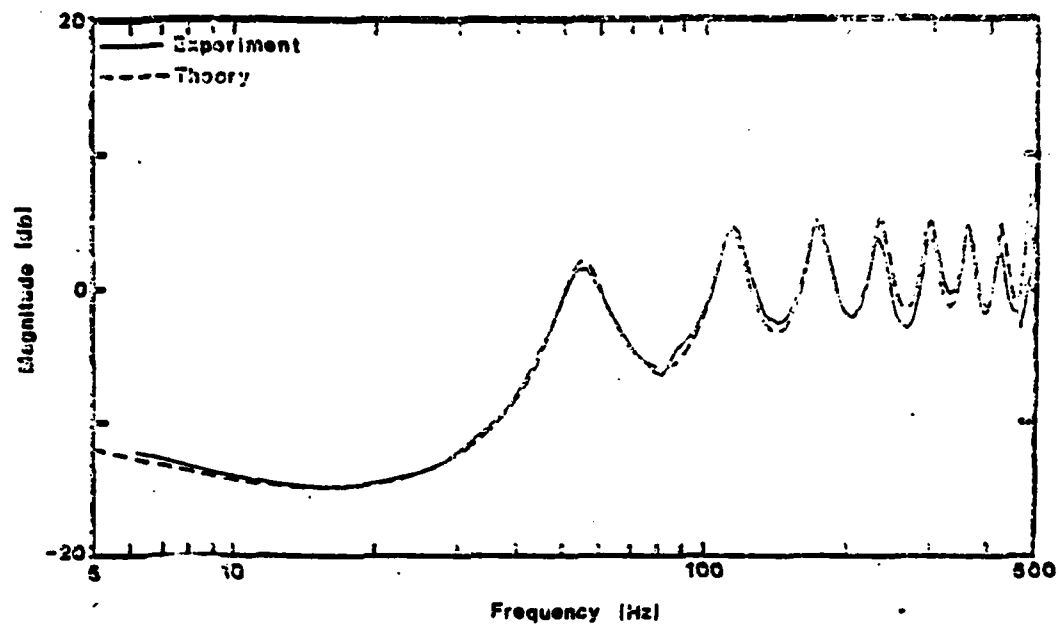
Data Set 48. Line with Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Resistor #3,  $\lambda = 315$  mm,  $d = 2.37$  mm)



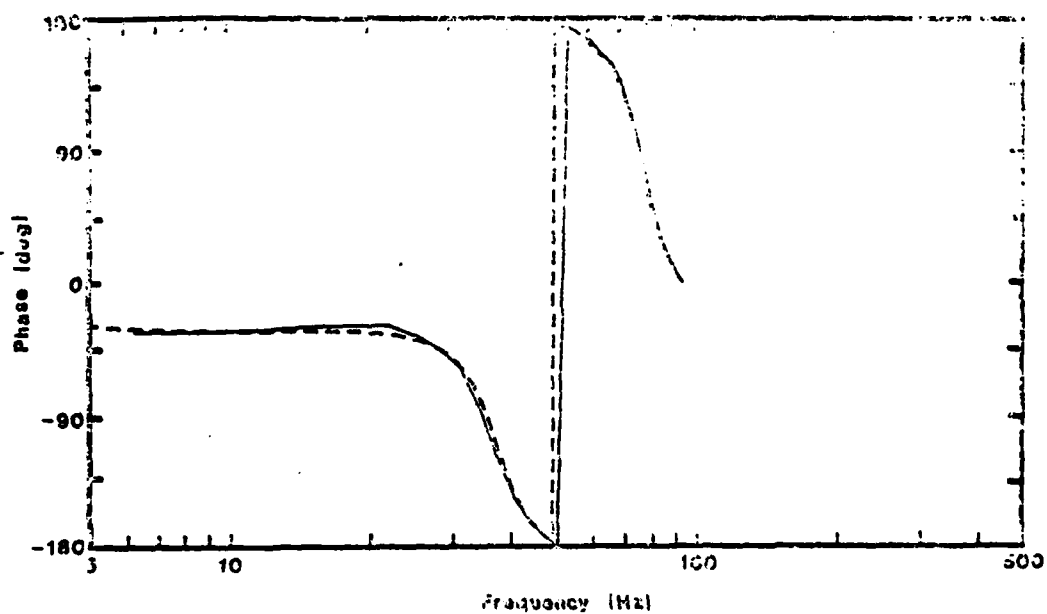
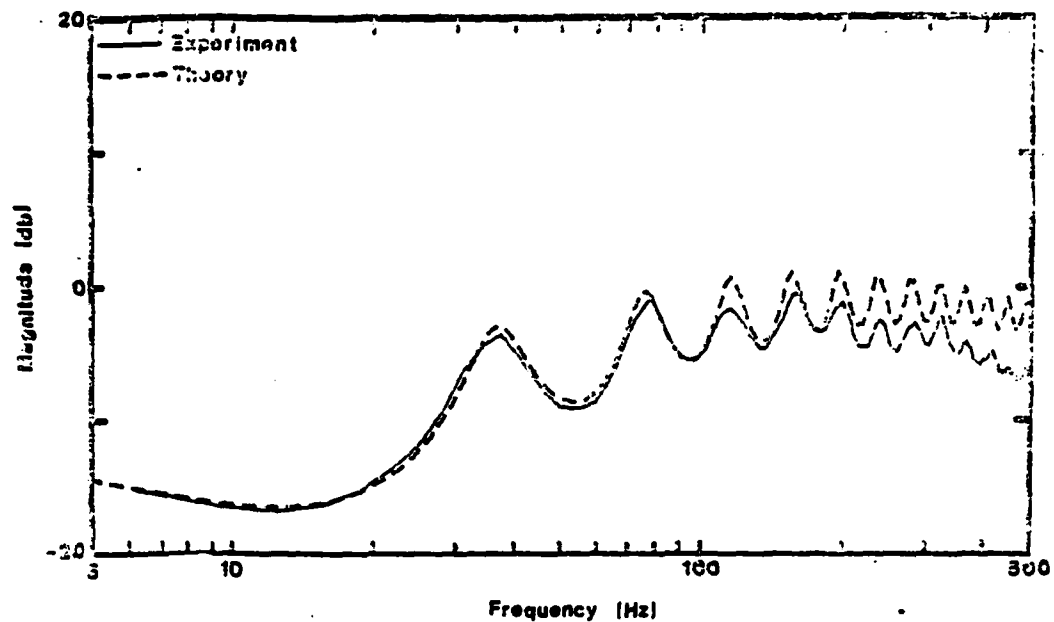
Data Set 49. Line with Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 1.7$  mm; Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



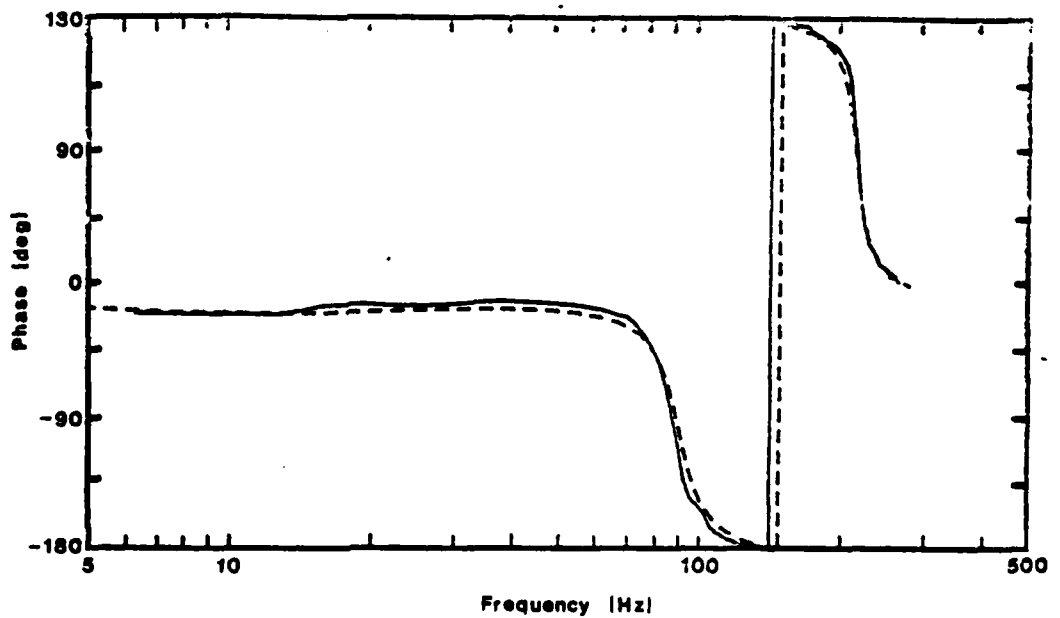
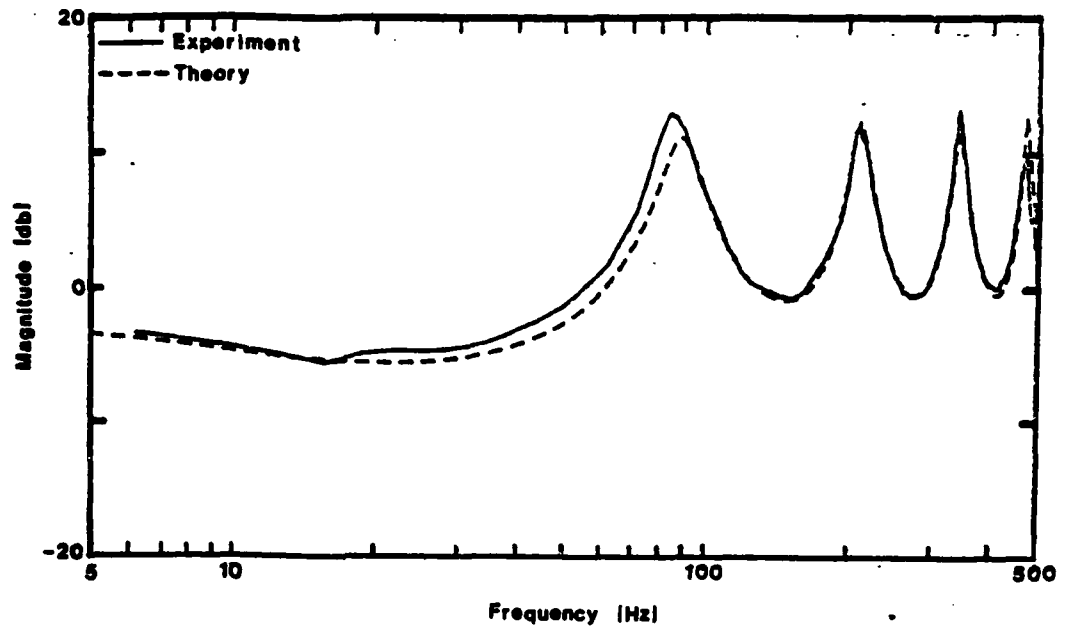
Data Set 50. Line with Load Impedance  
 ( $l = 4.8$  m,  $d = 4.8$  mm; Resistor #8,  $l = 315$  mm,  $d = 2.37$  mm)



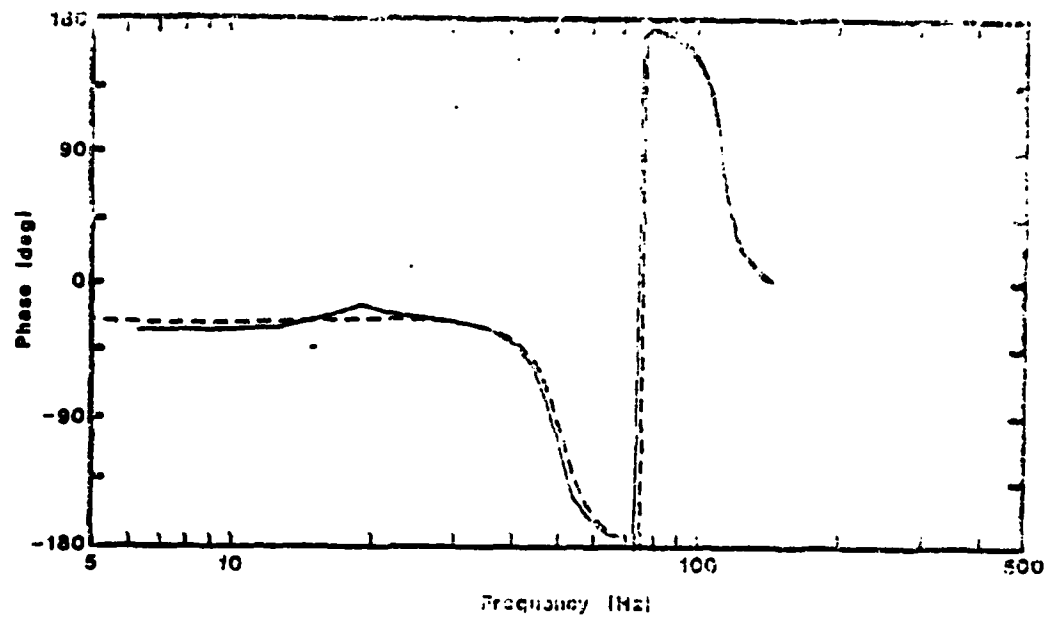
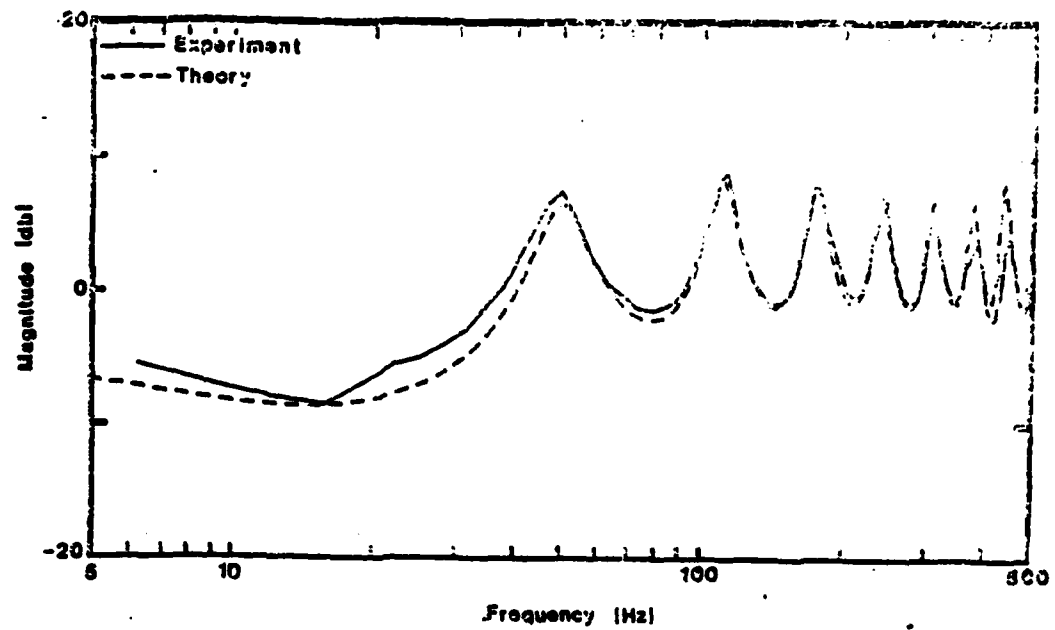
Data Set 51. Line with Load Impedance  
( $l = 9.6$  m,  $d = 4.8$  mm; Resistor #8,  $l = 315$  mm,  $d = 2.37$  mm)



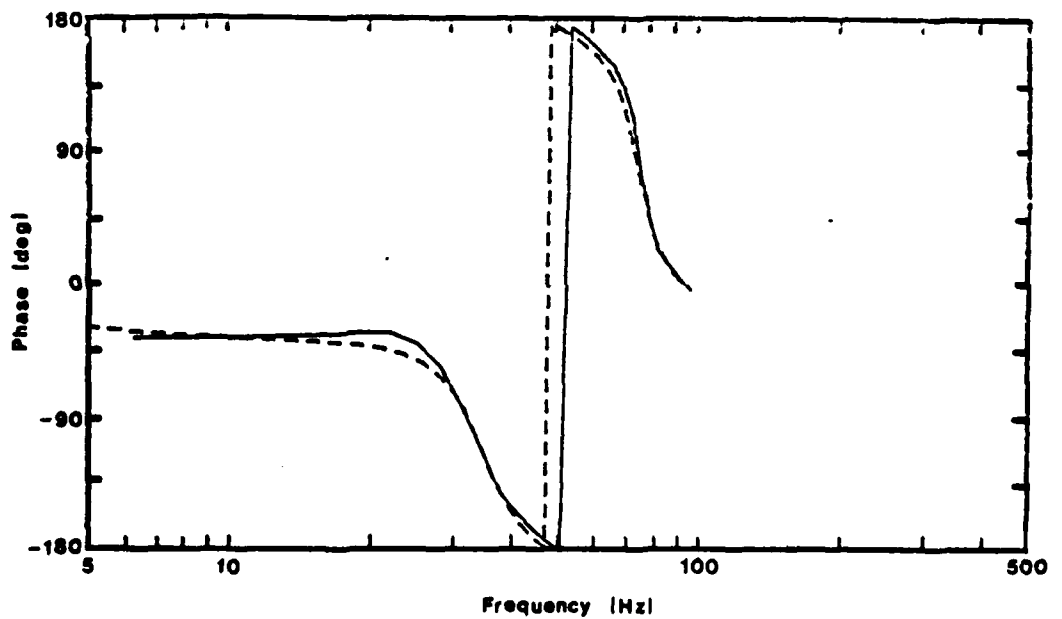
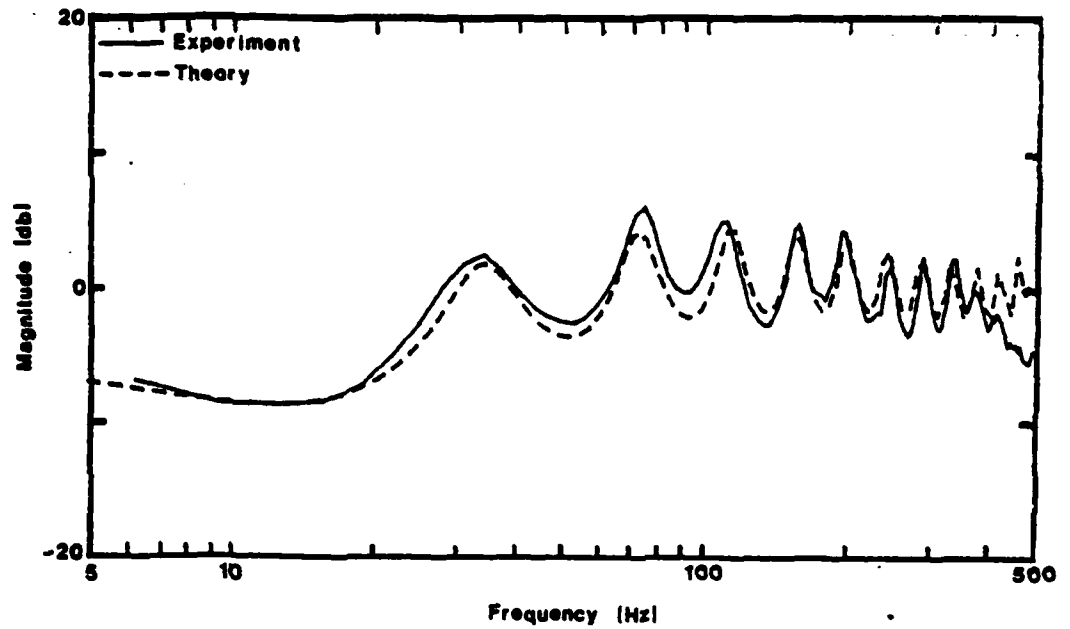
Data Set 52. Line with Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



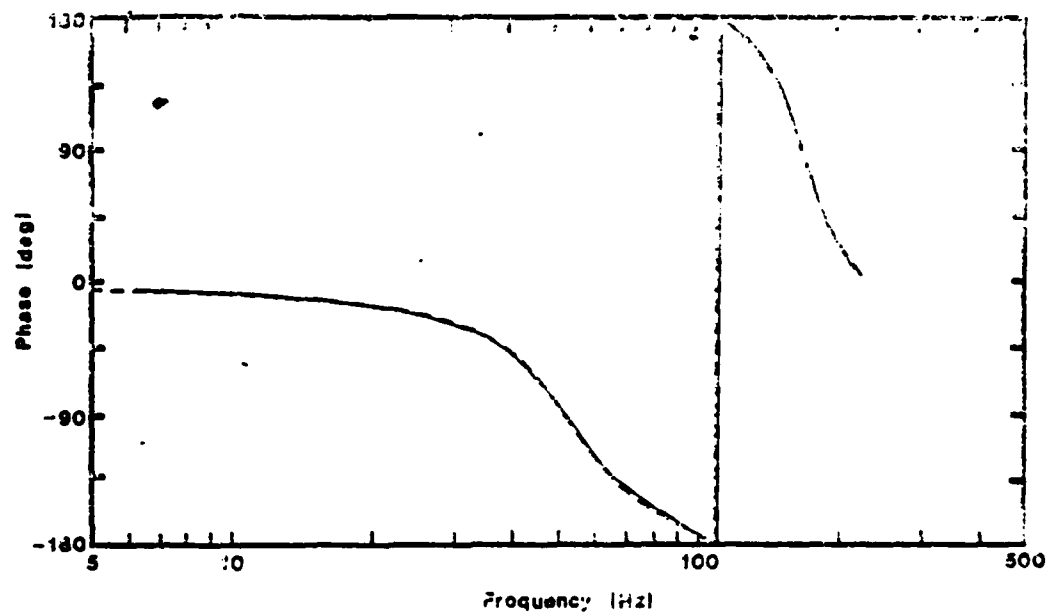
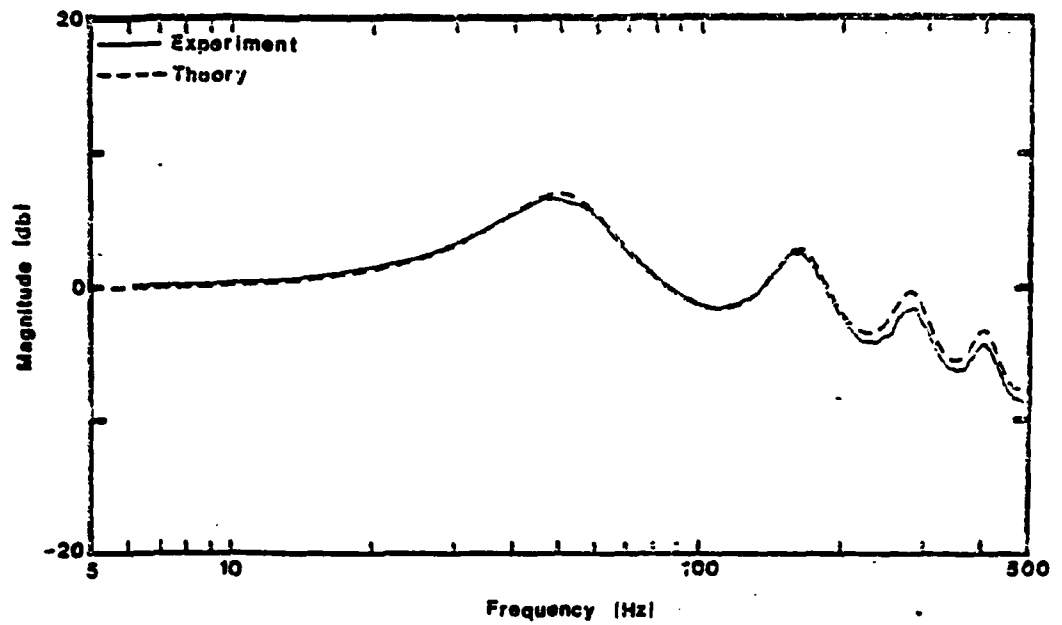
Data Set 53. Line with Load Impedance  
 ( $\ell = 1.0$  m,  $d = 7.6$  mm; Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



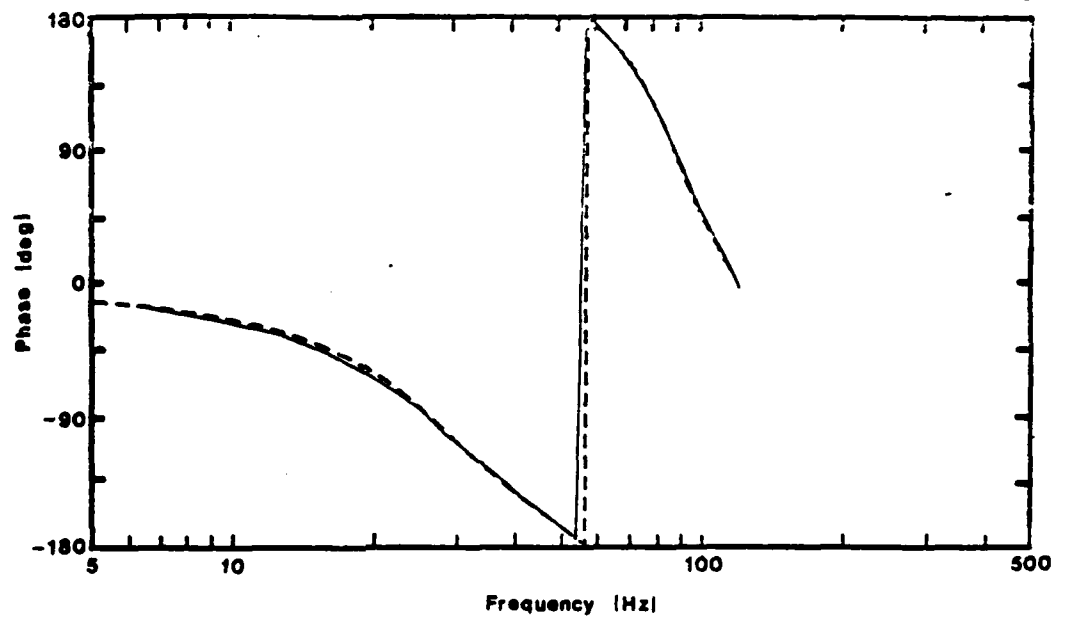
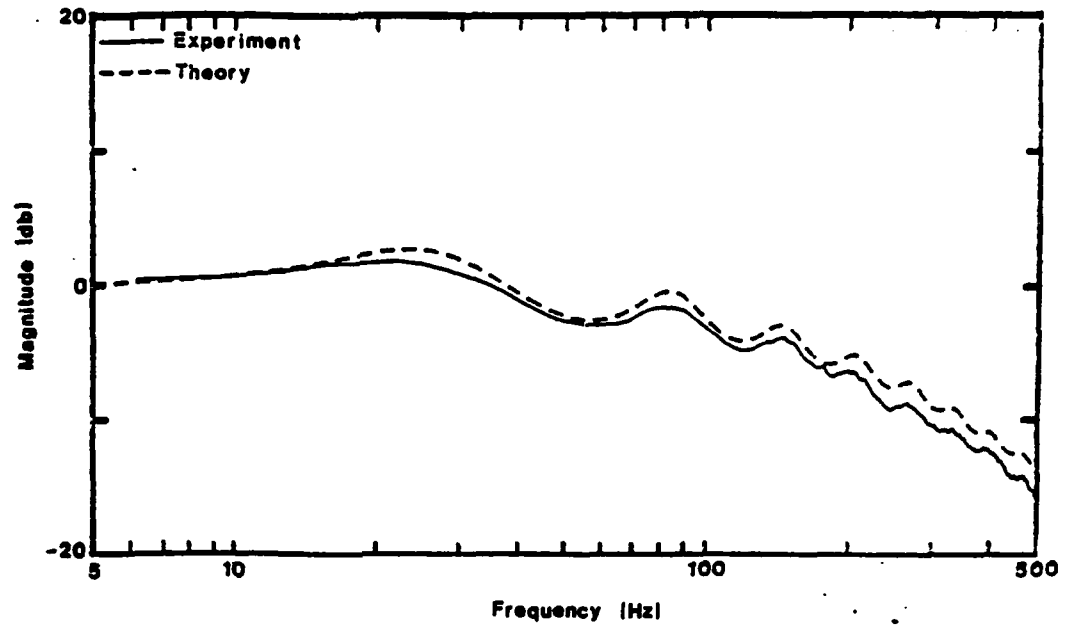
Data Set 54. Line with Load Impedance  
 $(\lambda = 9.6 \text{ m}, d = 7.6 \text{ mm}; \text{Resistor \#8}, \lambda = 315 \text{ mm}, d = 2.37 \text{ mm})$



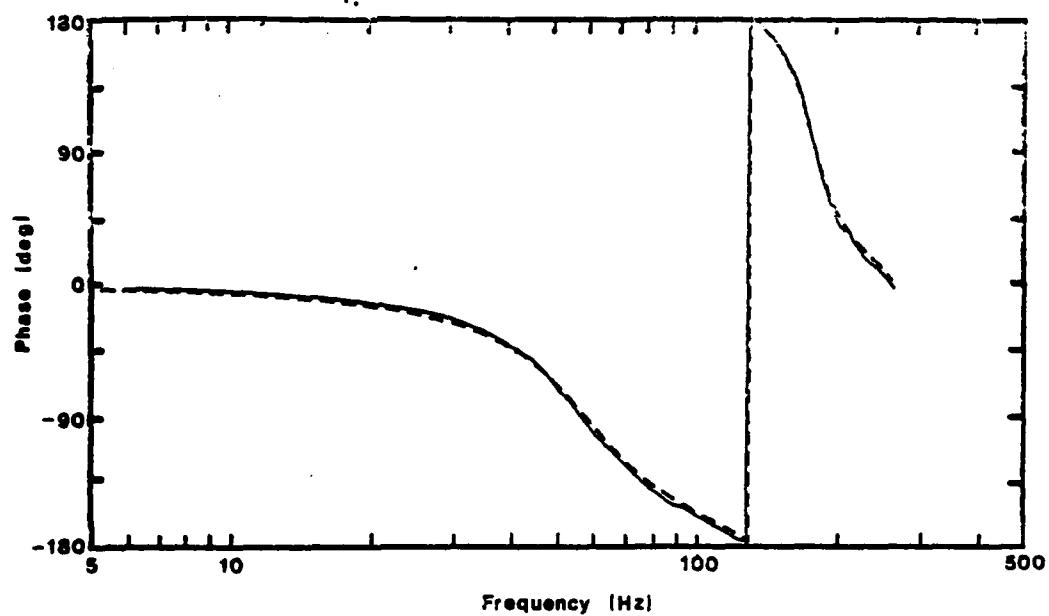
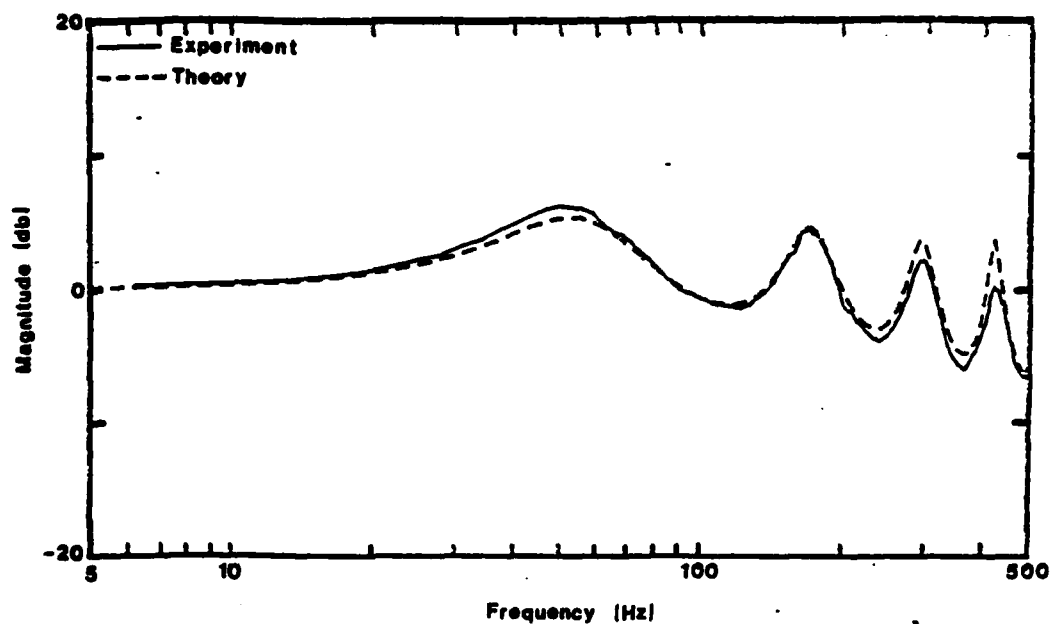
Data Set 55. Line with Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



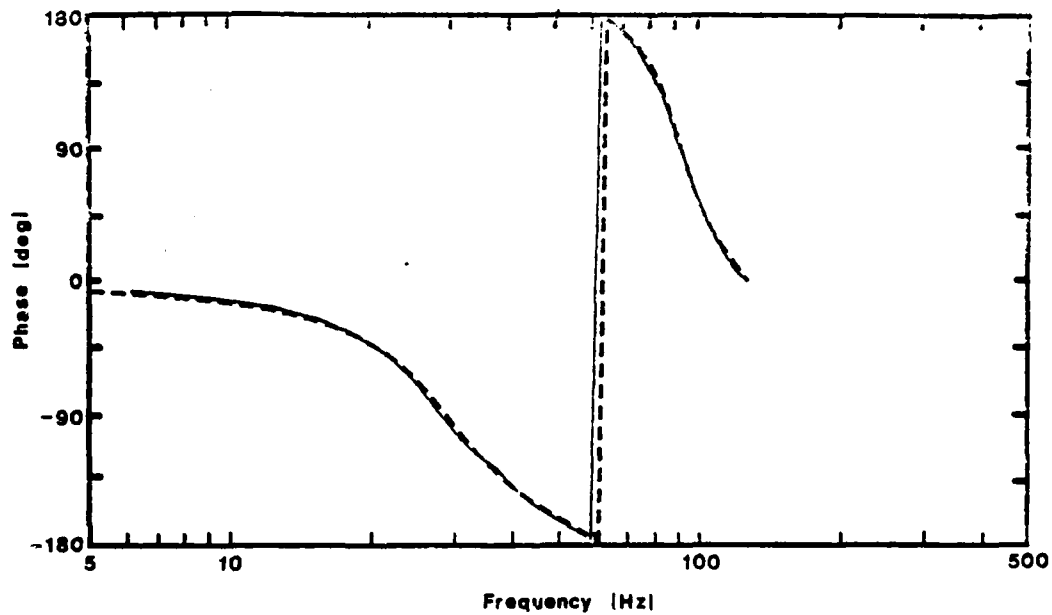
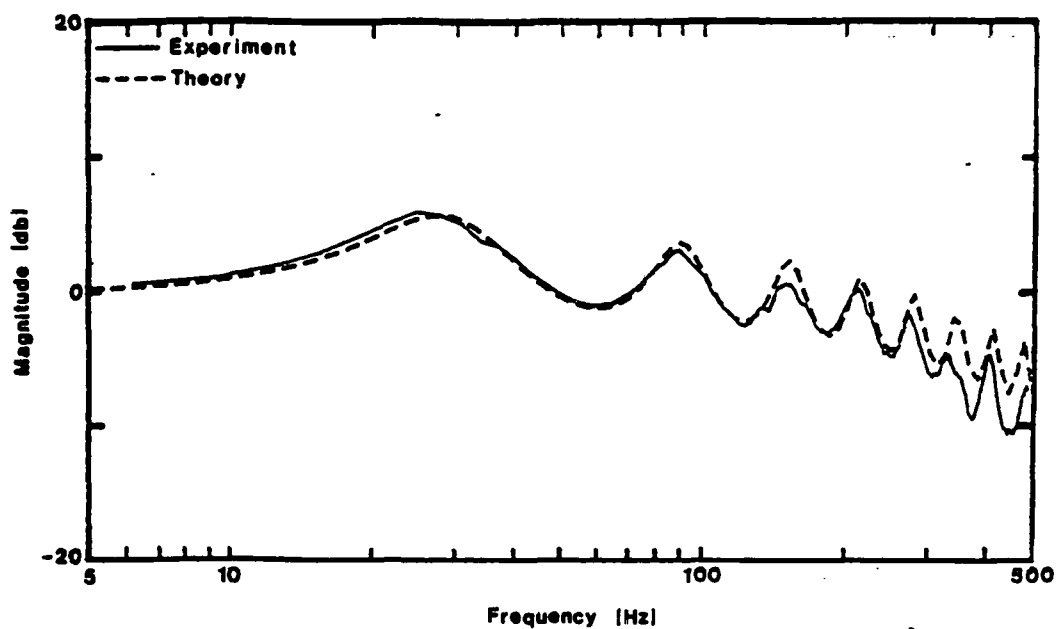
Data Set 56. Line with Source Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Resistor #2, 4 tubes,  $\lambda = 53$  mm,  $d = .716$  mm)



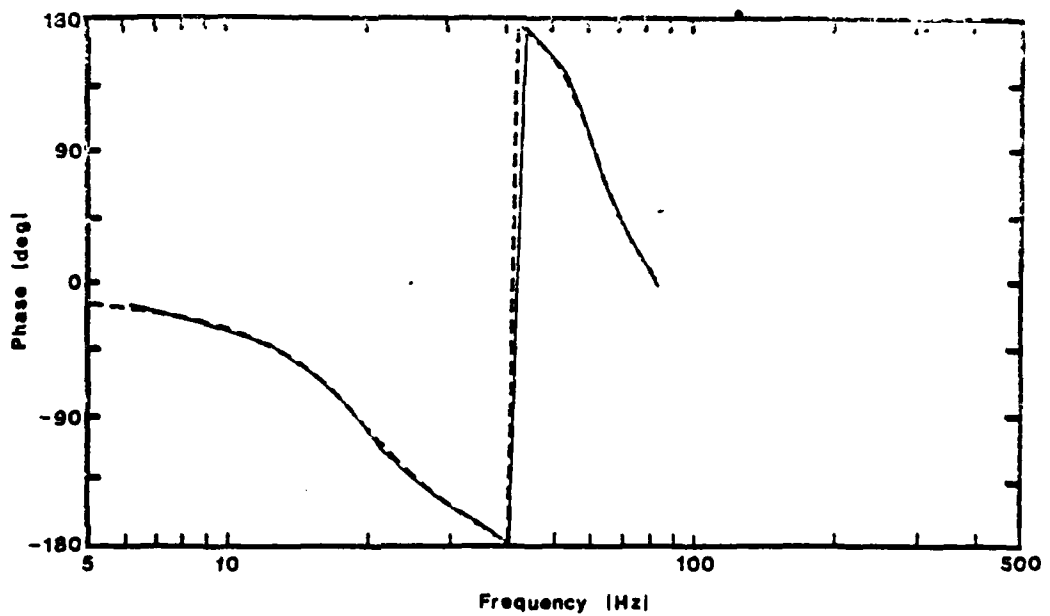
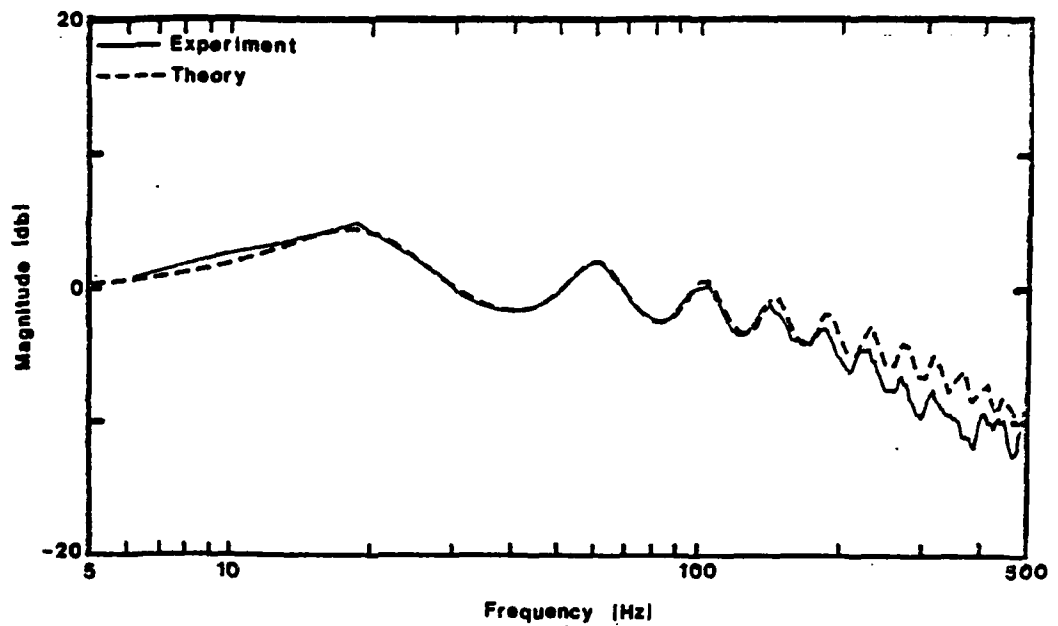
Data Set 57. Line with Source Impedance  
 ( $\lambda = 9.6$  m,  $d = 1.7$  mm; Resistor #2, 4 tubes,  $\lambda = 53$  mm,  $d = .716$  mm)



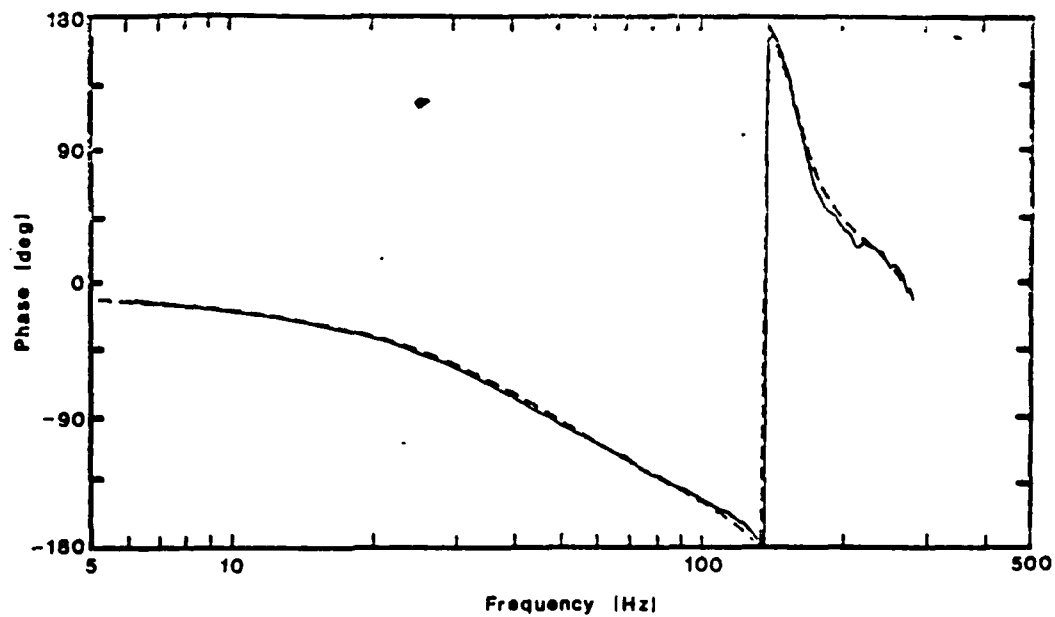
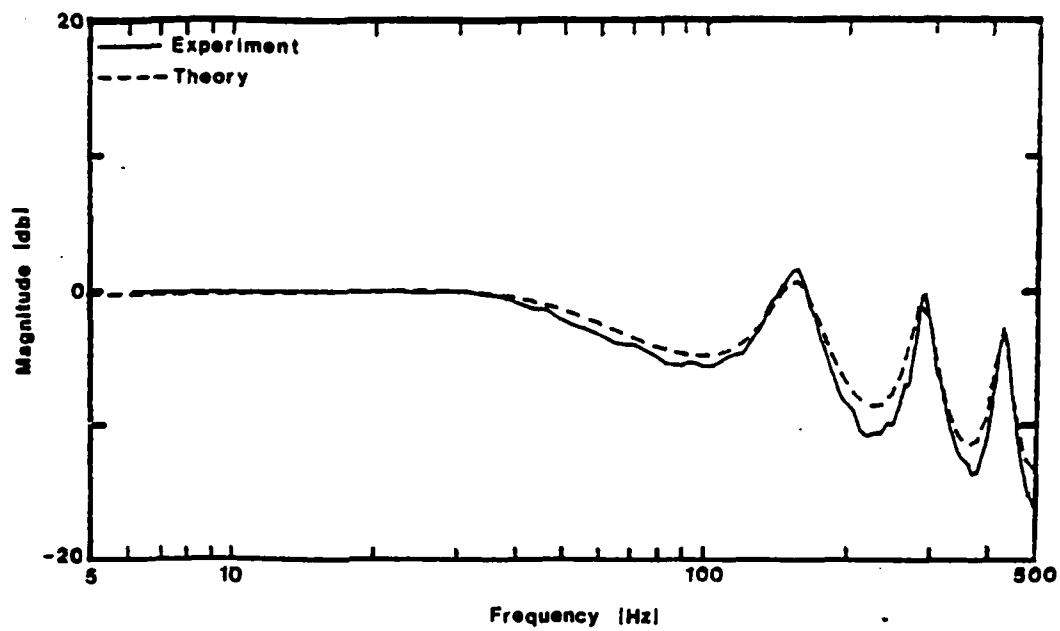
Data Set 58. Line with Source Impedance  
( $\ell = 4.8$  m,  $d = 4.8$  mm; Resistor #2, 4 tubes,  $\ell = 53$  mm,  $d = .716$  mm)



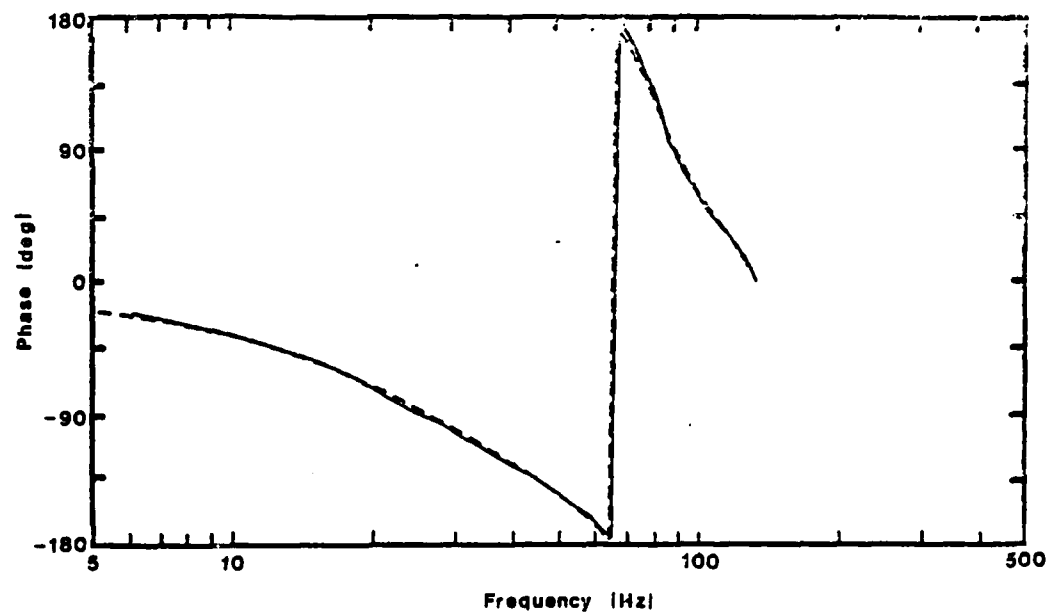
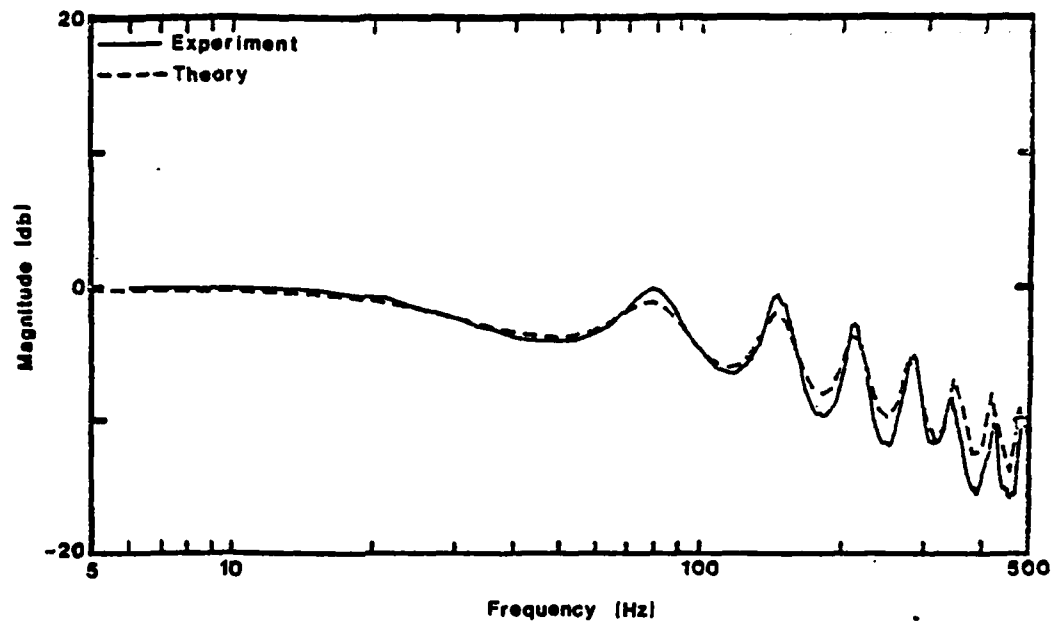
Data Set 59. Line with Source Impedance  
 ( $l = 9.6$  m,  $d = 4.8$  mm; Resistor #2, 4 tubes,  $l = 53$  mm,  $d = .716$  mm)



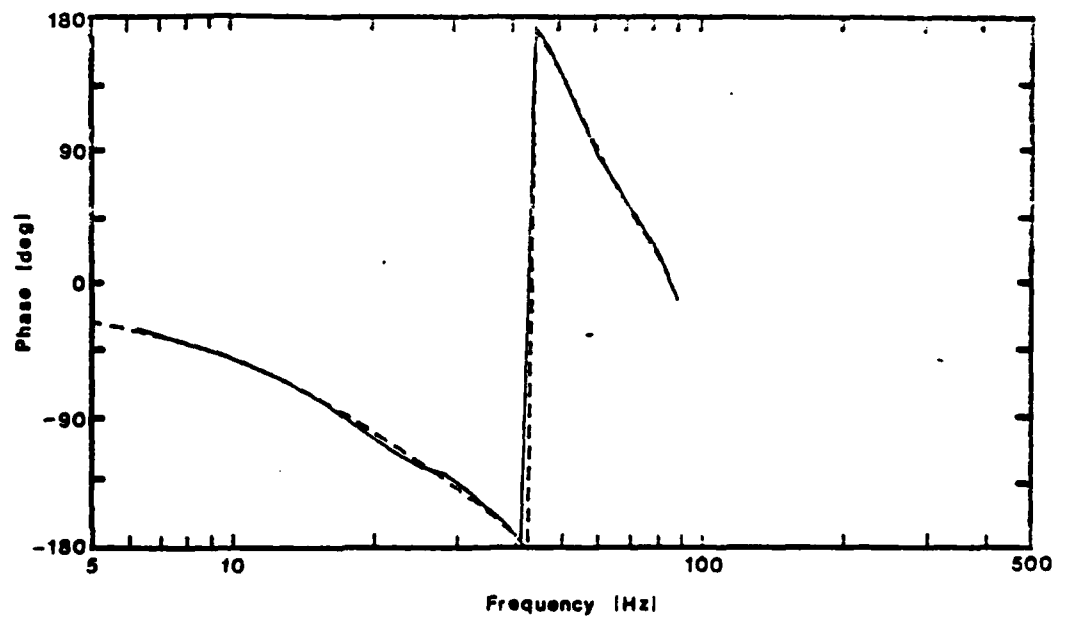
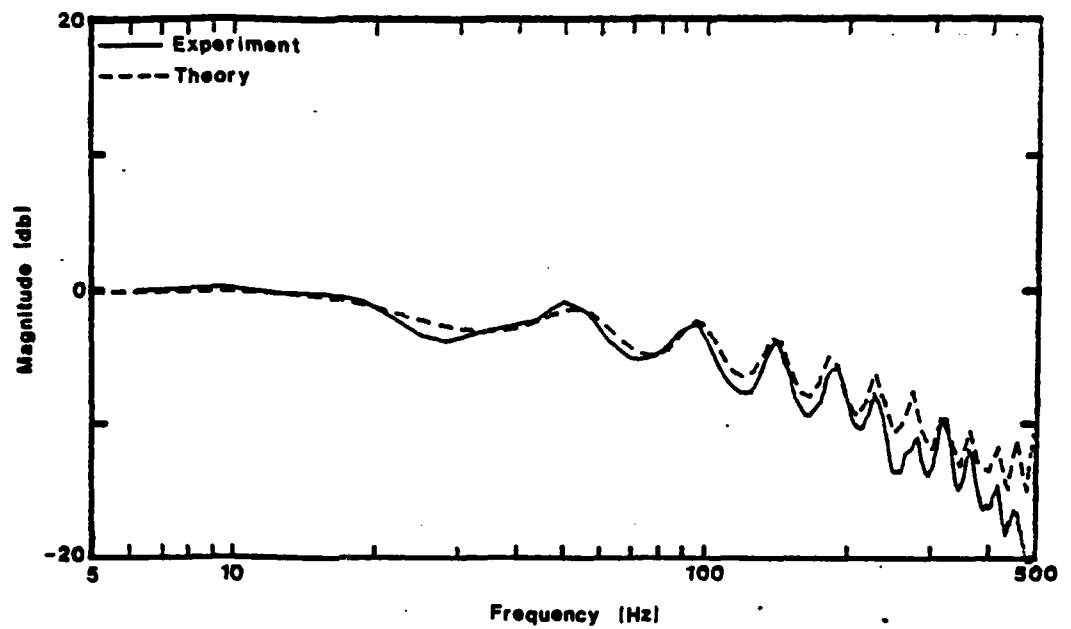
Data Set 60. Line with Source Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Resistor #2, 4 tubes,  $\ell = 53$  mm,  $d = .716$  mm)



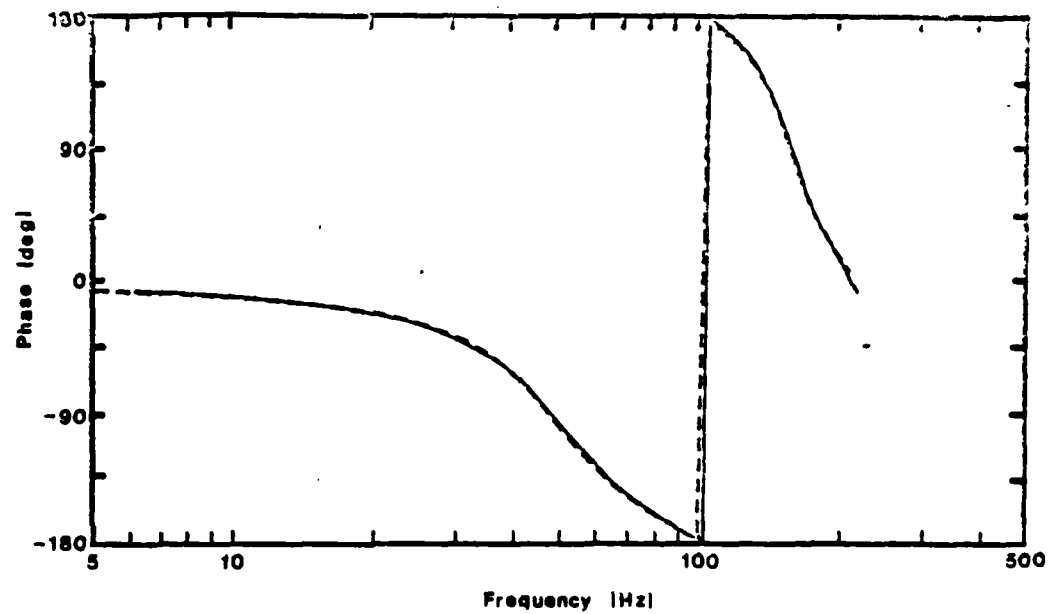
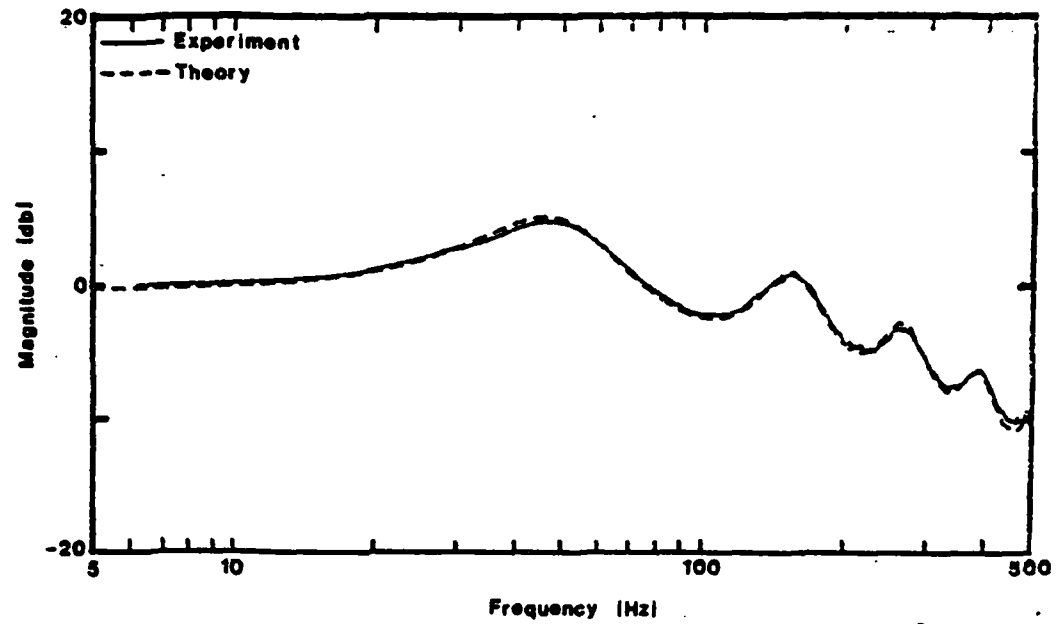
Data Set 61. Line with Source Impedance  
( $\lambda = 4.8$  m,  $d = 7.6$  mm; Resistor #2, 4 tubes,  $\lambda = 53$  mm,  $d = .716$  mm)



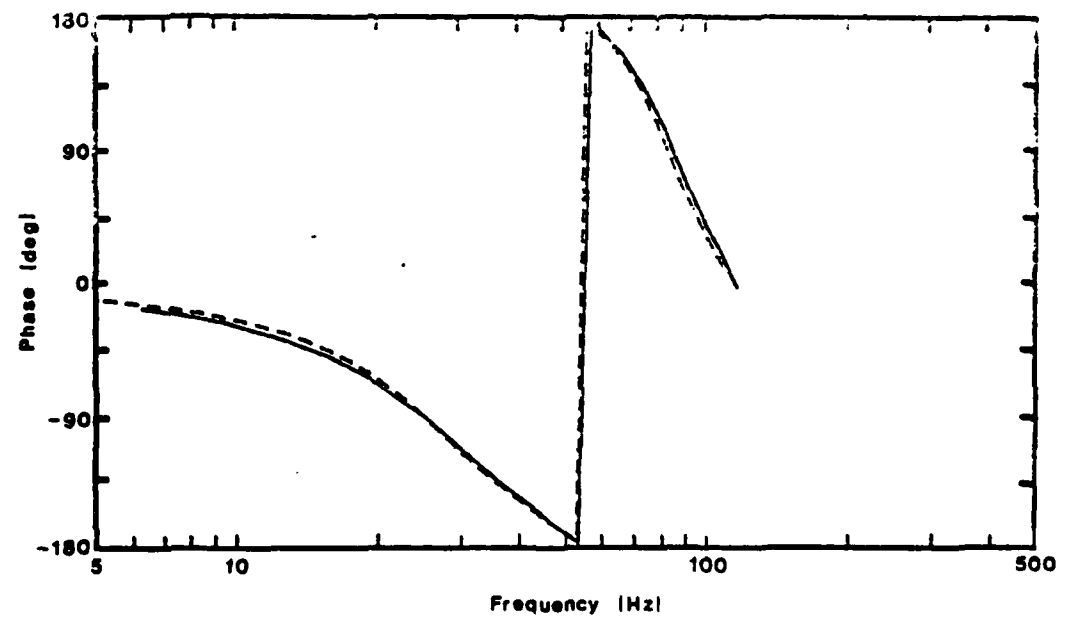
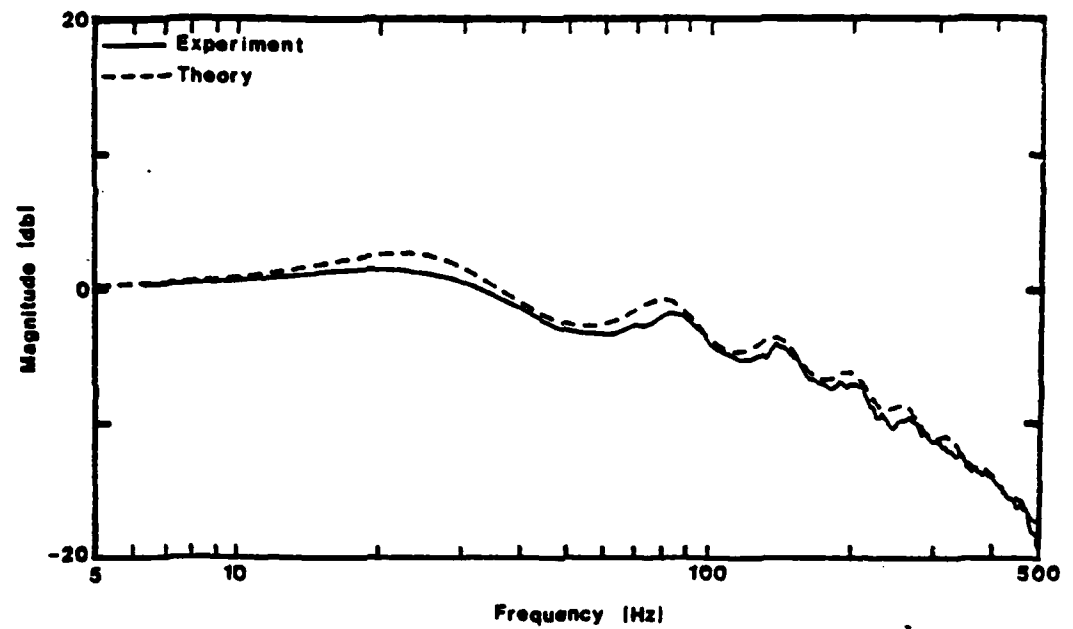
Data Set 62. Line with Source Impedance  
( $\ell = 9.6$  m,  $d = 7.6$  mm; Resistor #2, 4 tubes,  $\ell = 53$  mm,  $d = .716$  mm)



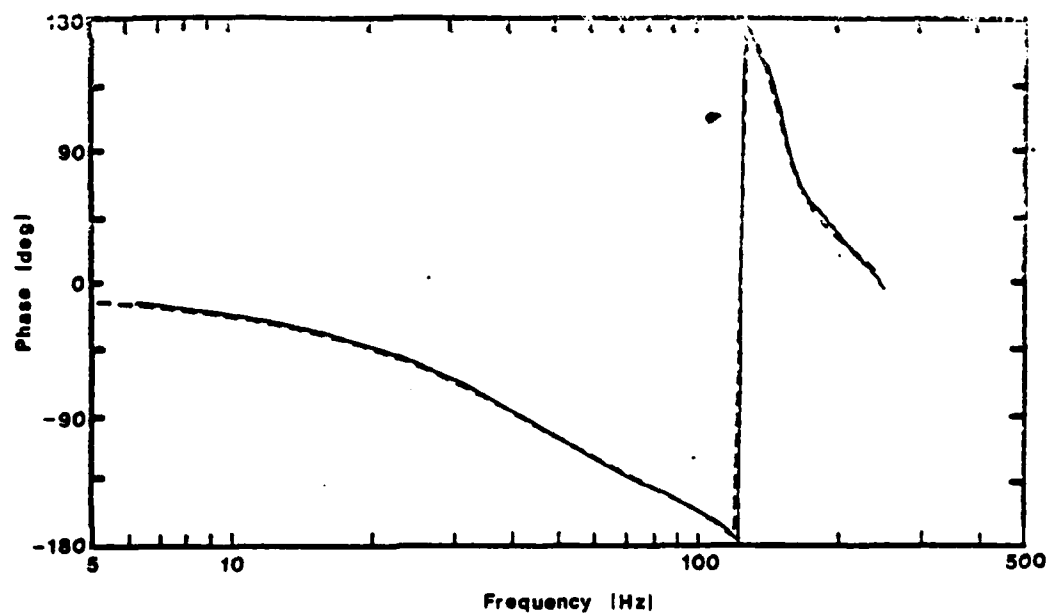
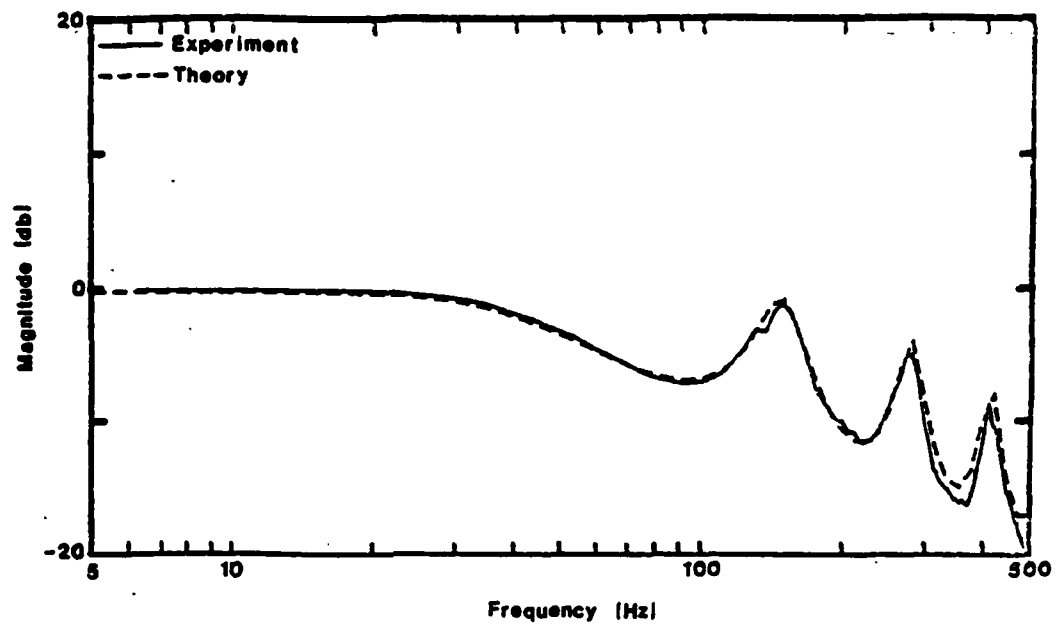
Data Set 63. Line with Source Impedance  
 ( $\lambda = 14.0$  cm,  $d = 7.6$  mm; Resistor #2, 4 tubes,  $\lambda = 53$  mm,  $d = .716$  mm)



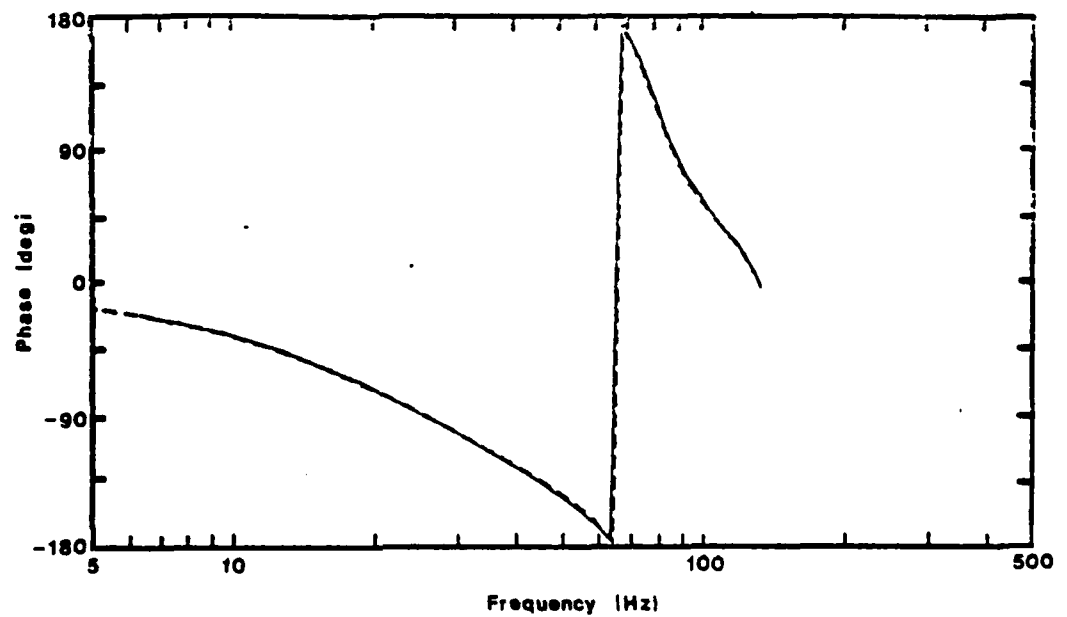
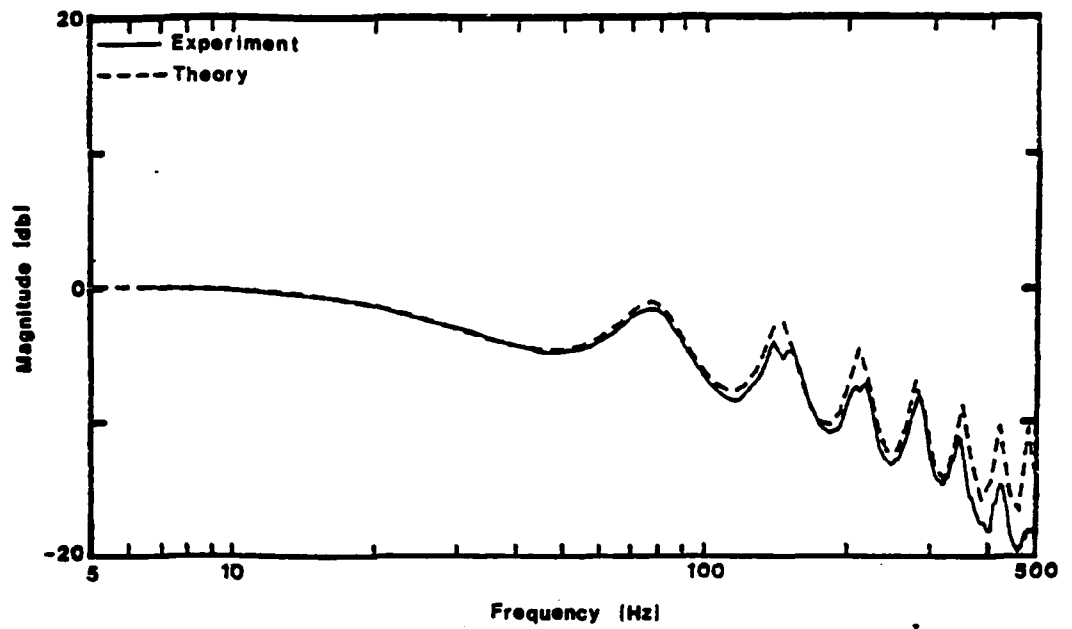
Data Set 64. Line with Source Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



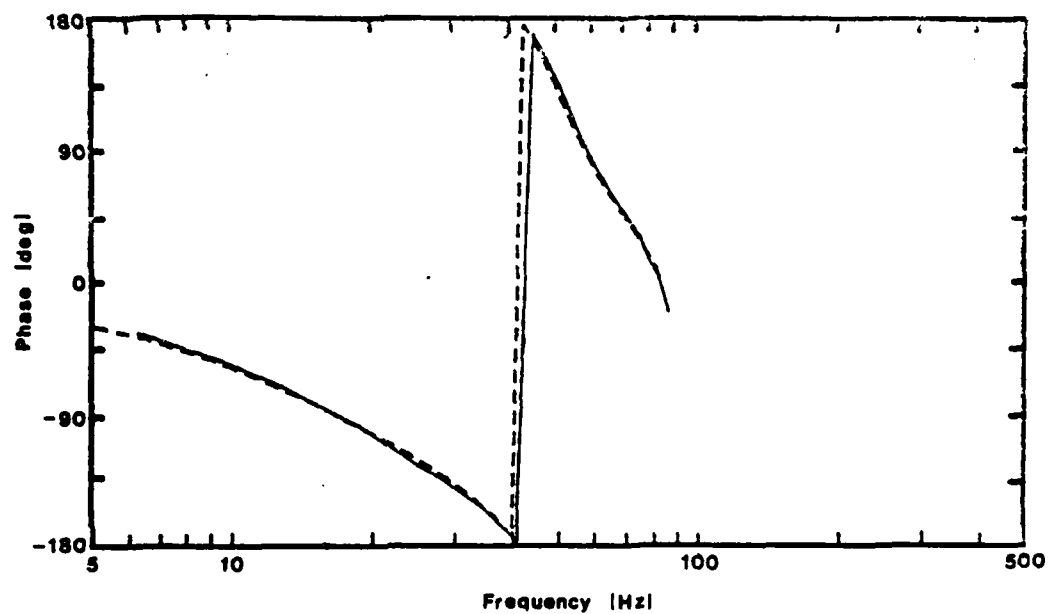
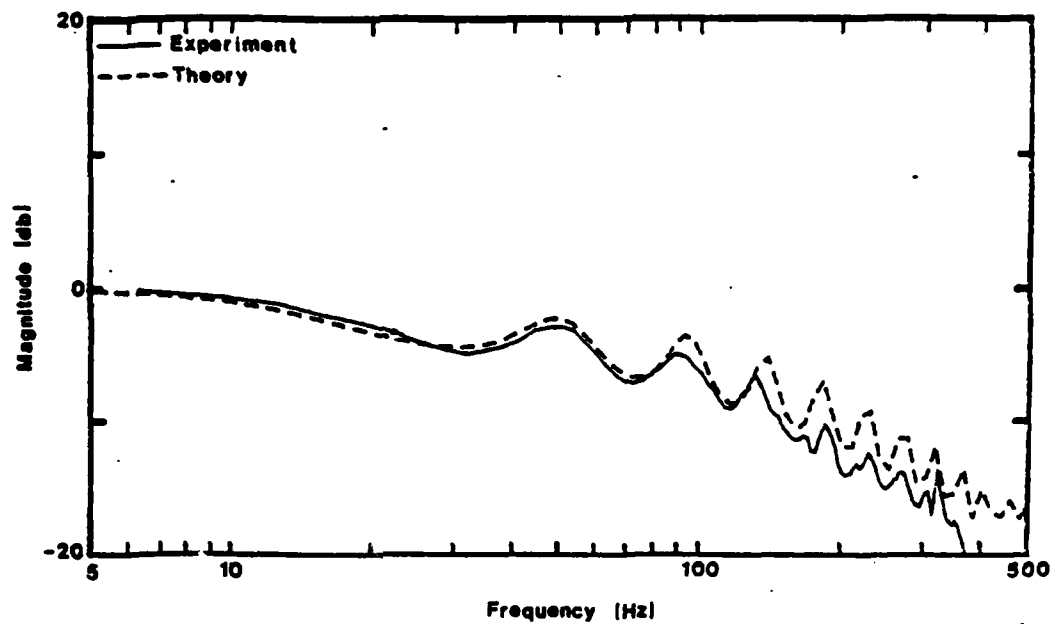
Data Set 65. Line with Source Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



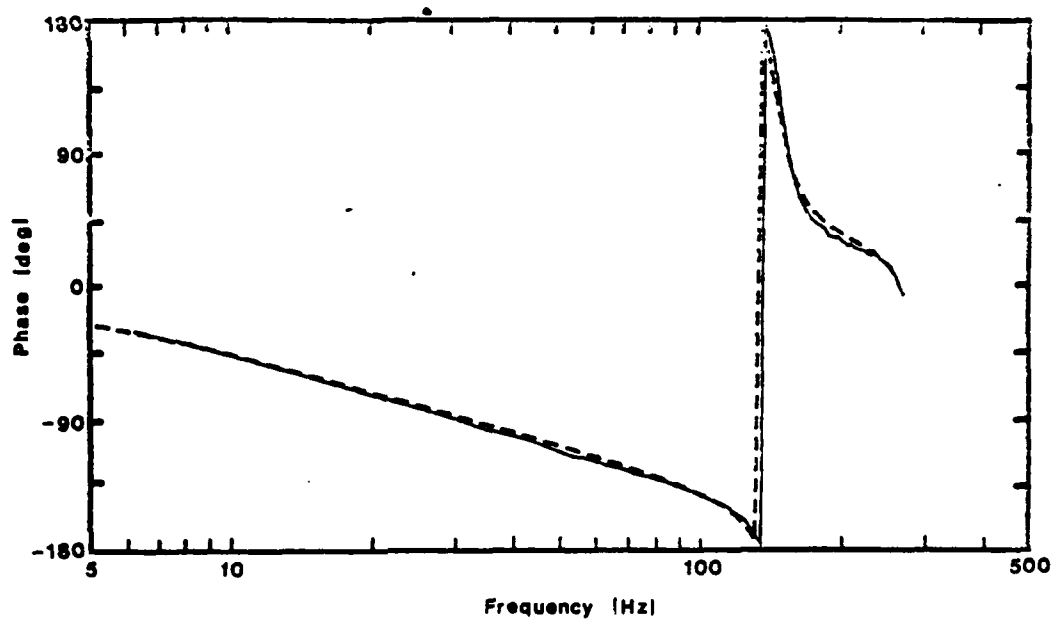
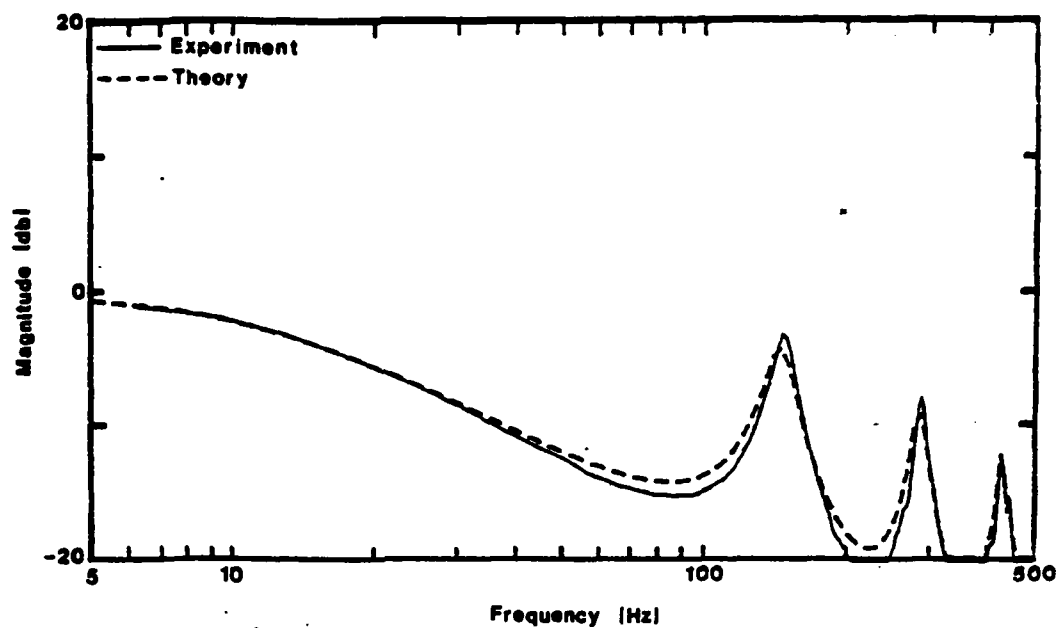
Data Set 66. Line with Source Impedance  
( $\ell = 4.8$  m,  $d = 4.8$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



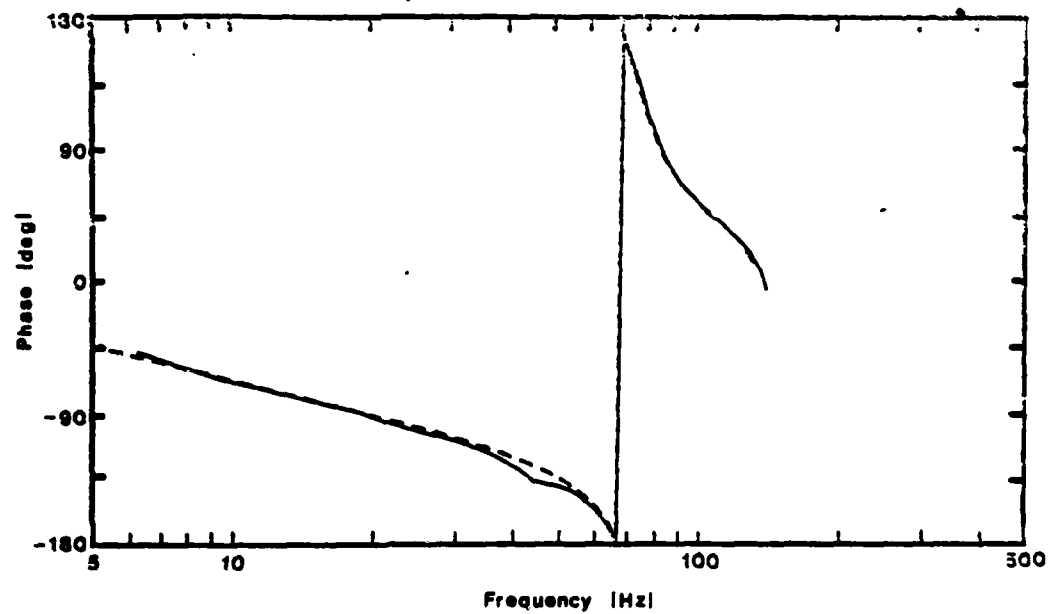
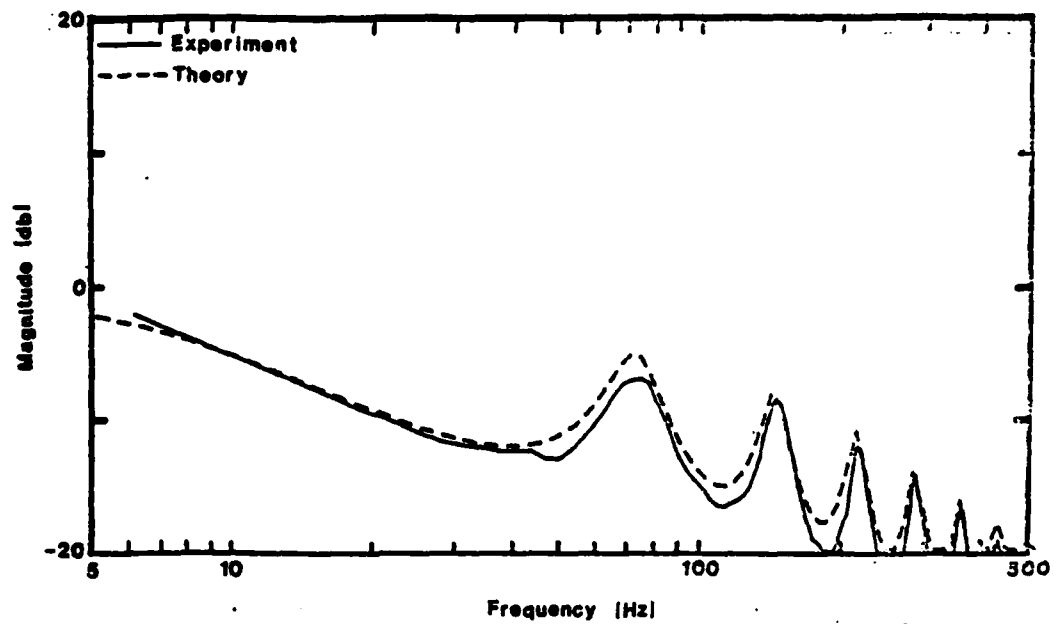
Data Set 67. Line with Source Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



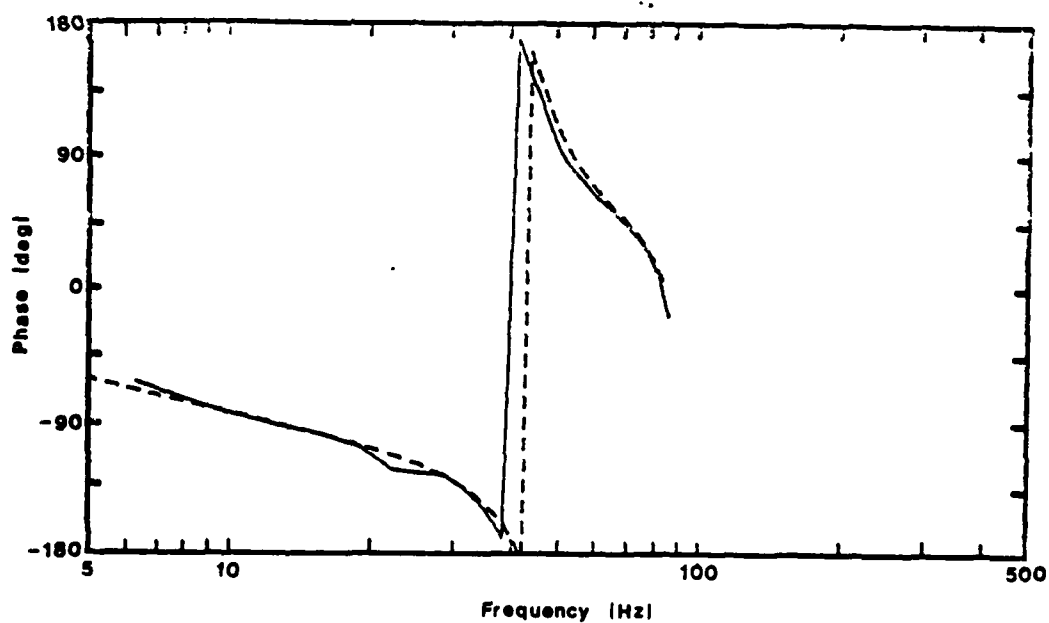
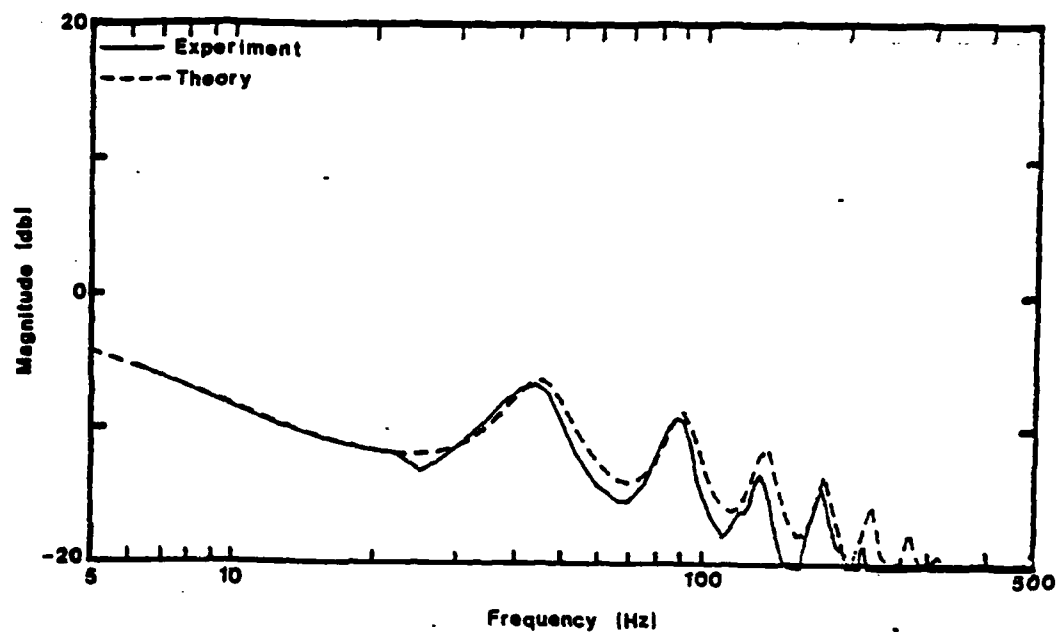
Data Set 68. Line with Source Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



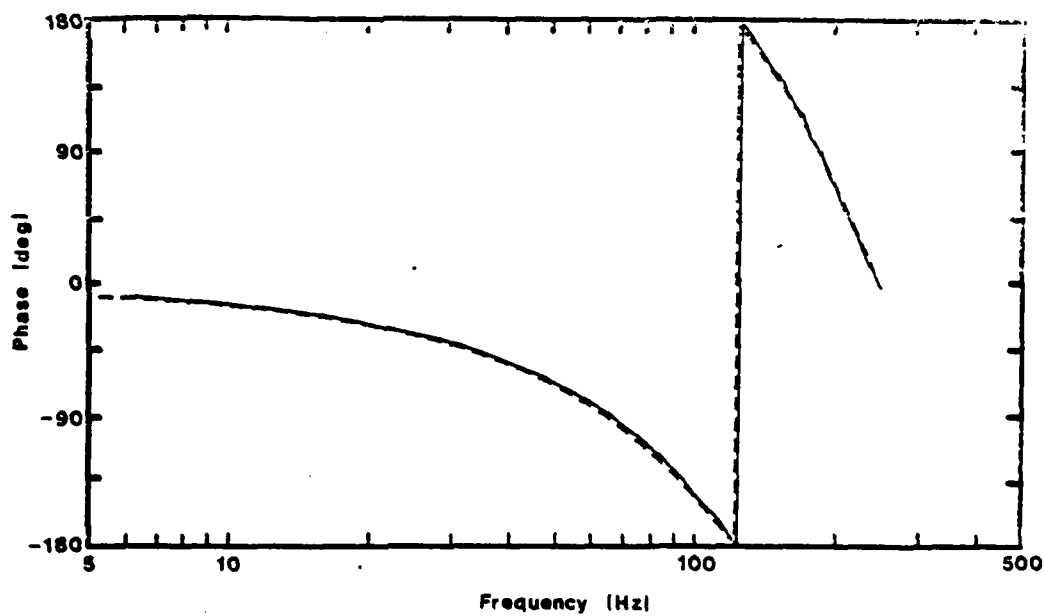
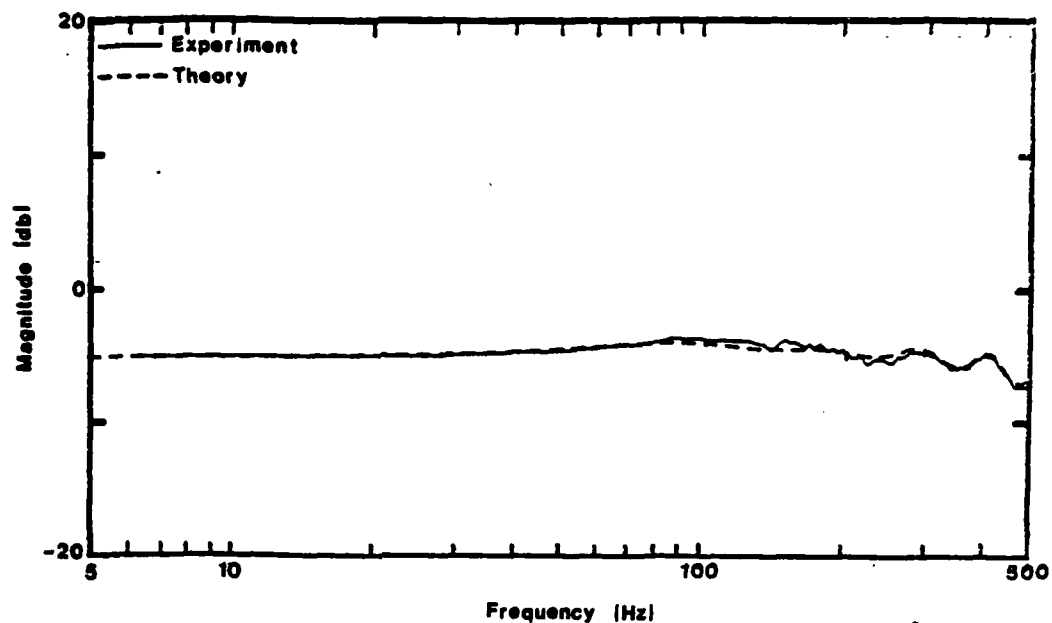
Data Set 69. Line with Source Impedance  
( $\ell = 4.8$  m,  $d = 7.6$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



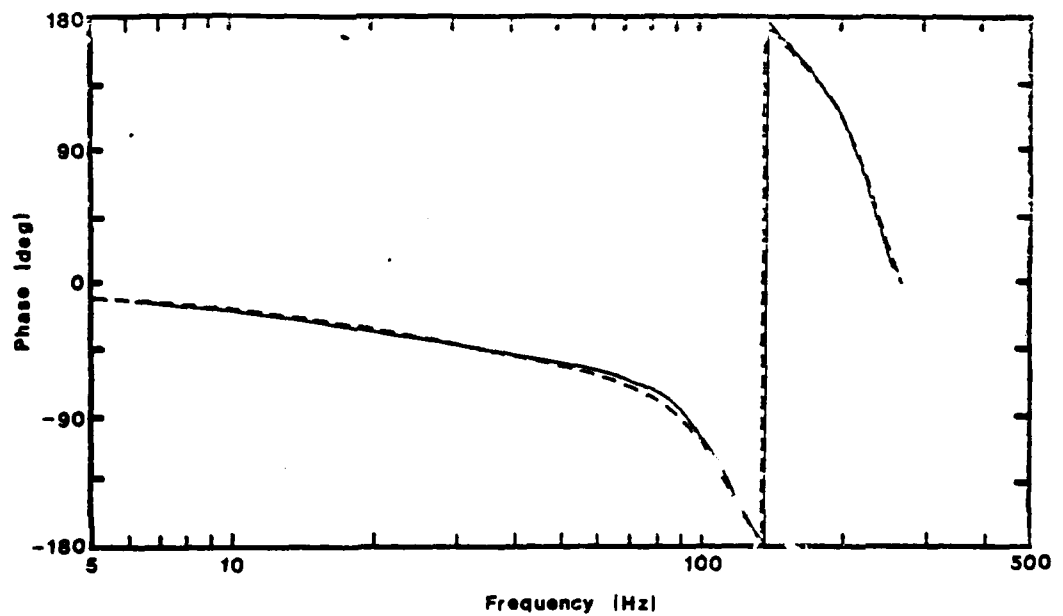
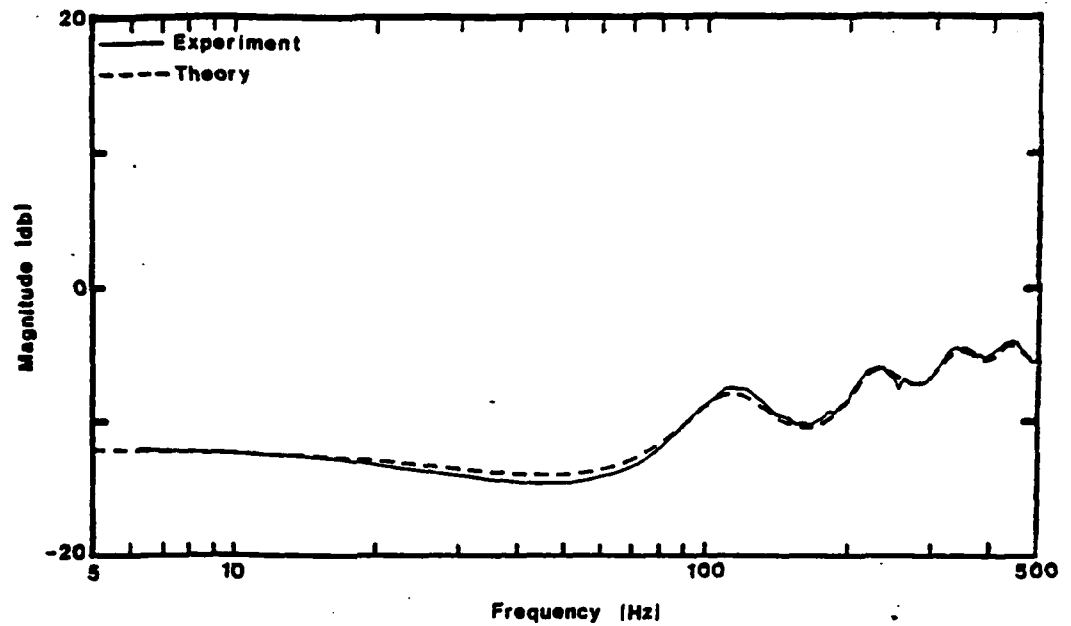
Data Set 70. Line with Source Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Resistor #1,  $\lambda = 53$  mm,  $d = .716$  mm)



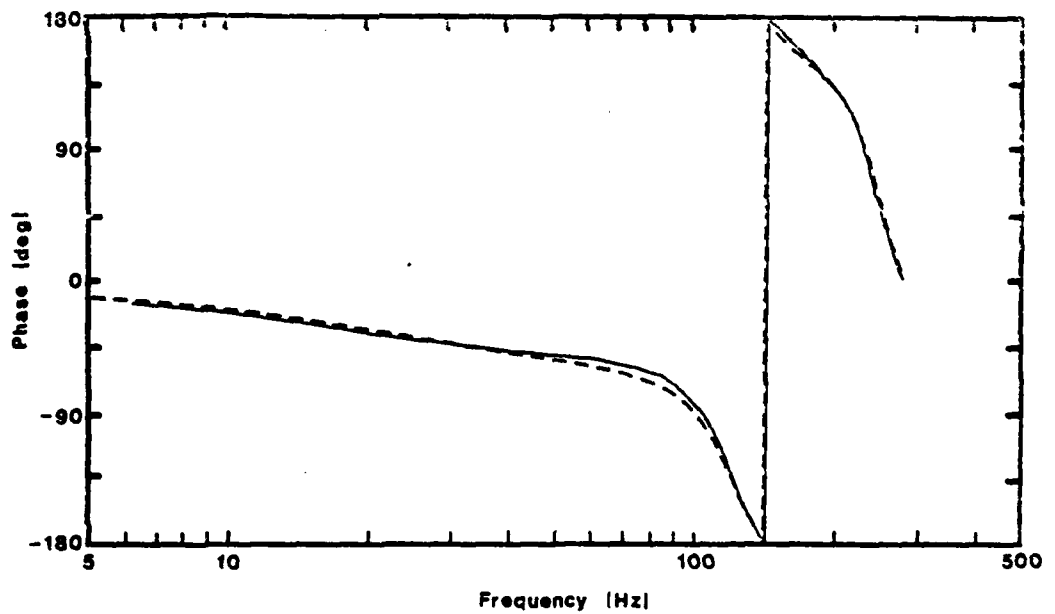
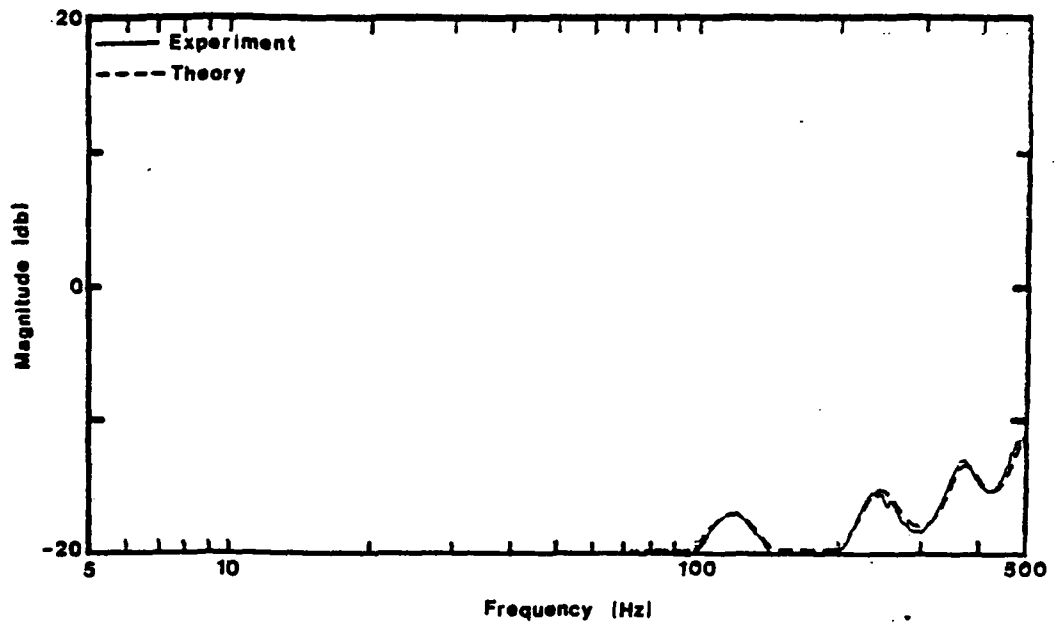
Data Set 71. Line with Source Impedance  
 ( $\ell = 14.8$  m,  $d = 7.6$  mm; Resistor #1,  $\ell = 53$  mm,  $d = .716$  mm)



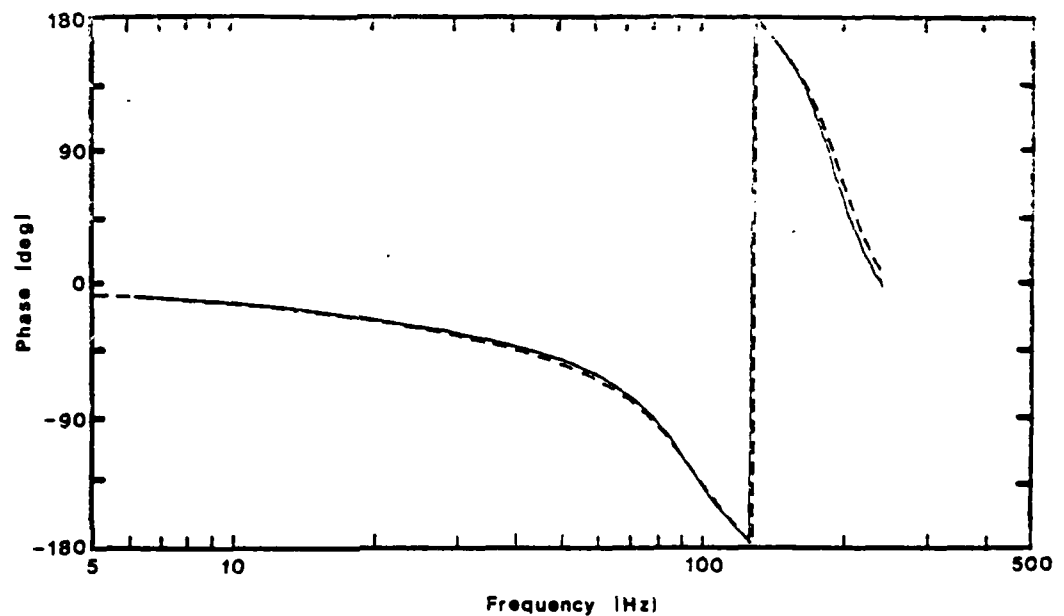
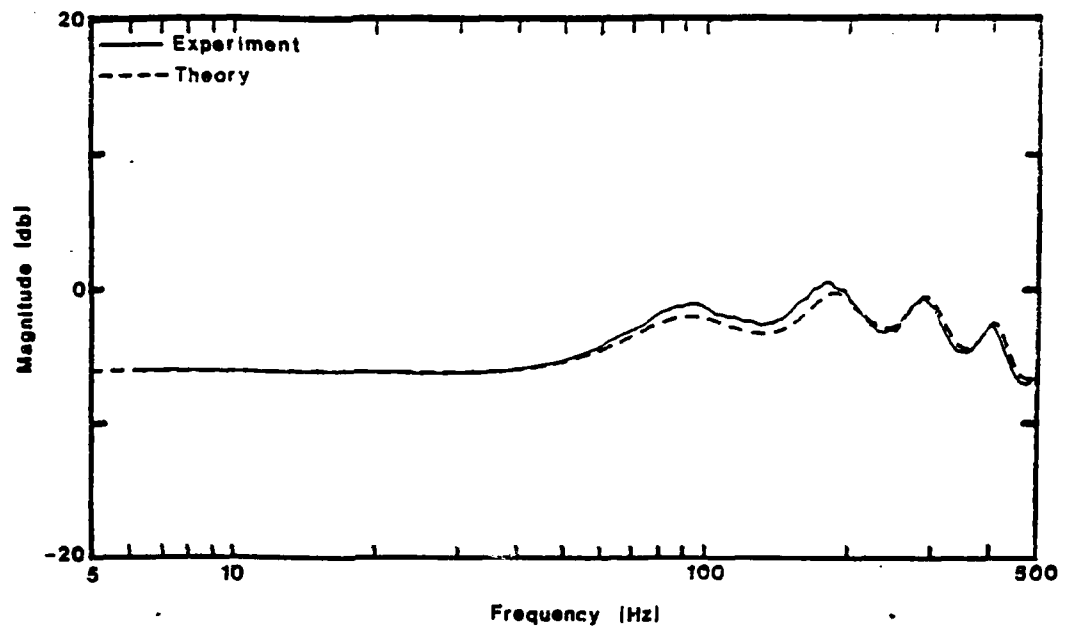
Data Set 72. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



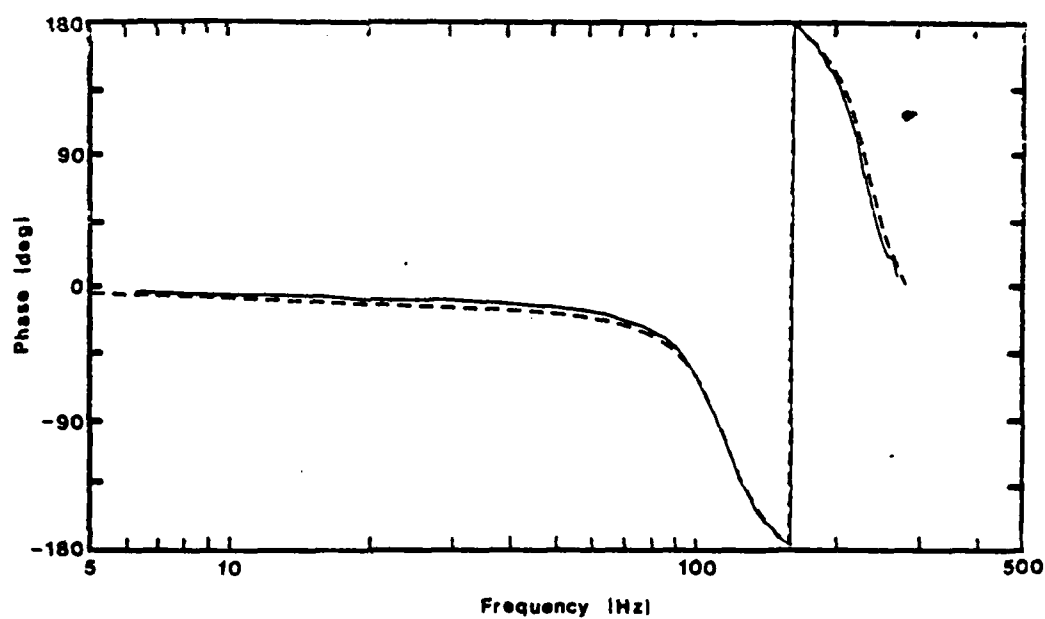
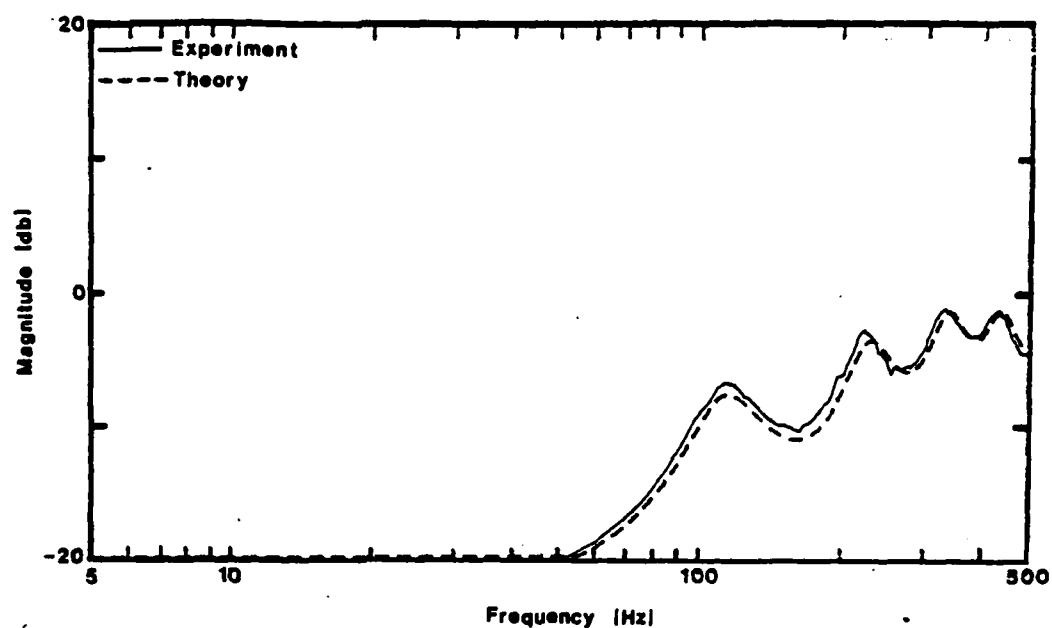
Data Set 73. Line with Source Impedance and Load Impedance  
( $l = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $l = 50$  mm,  $d = .716$  mm)



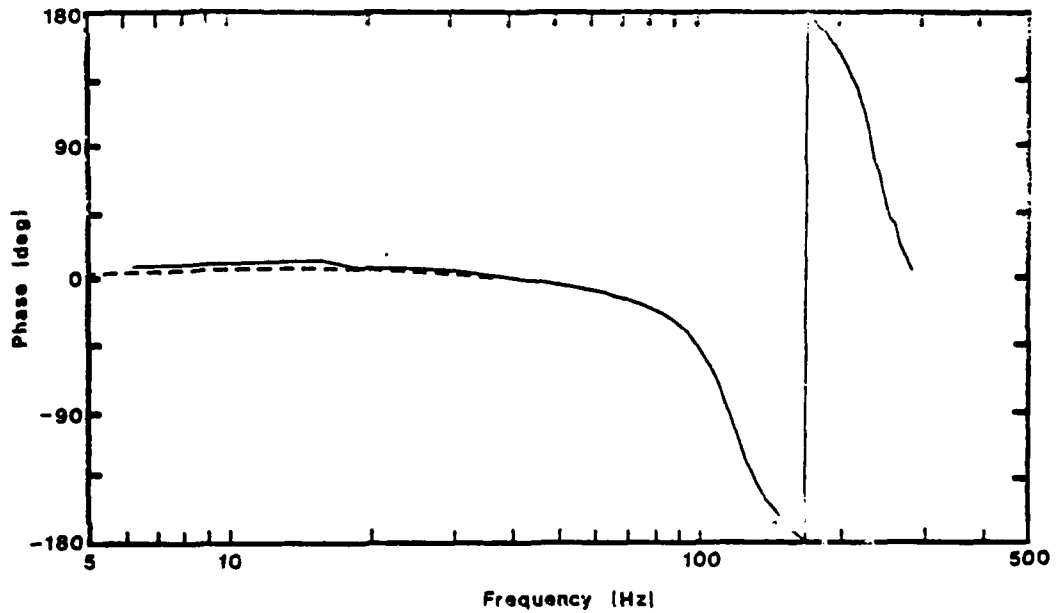
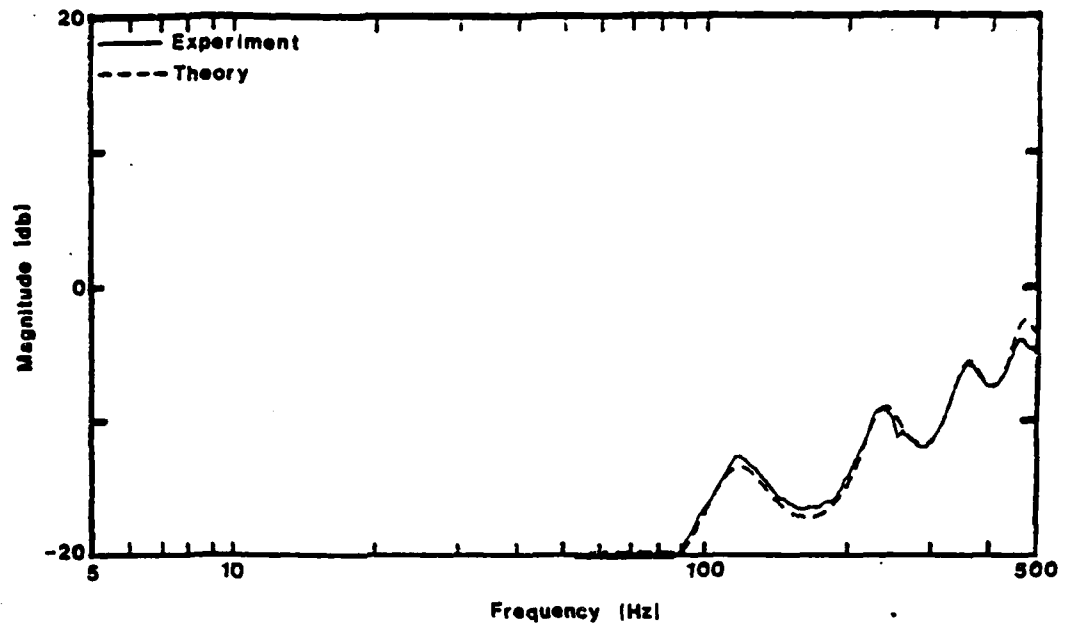
Data Set 74. Line with Source Impedance and Load Impedance  
 ( $l = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $l = 52$  mm,  $d = .716$  mm)



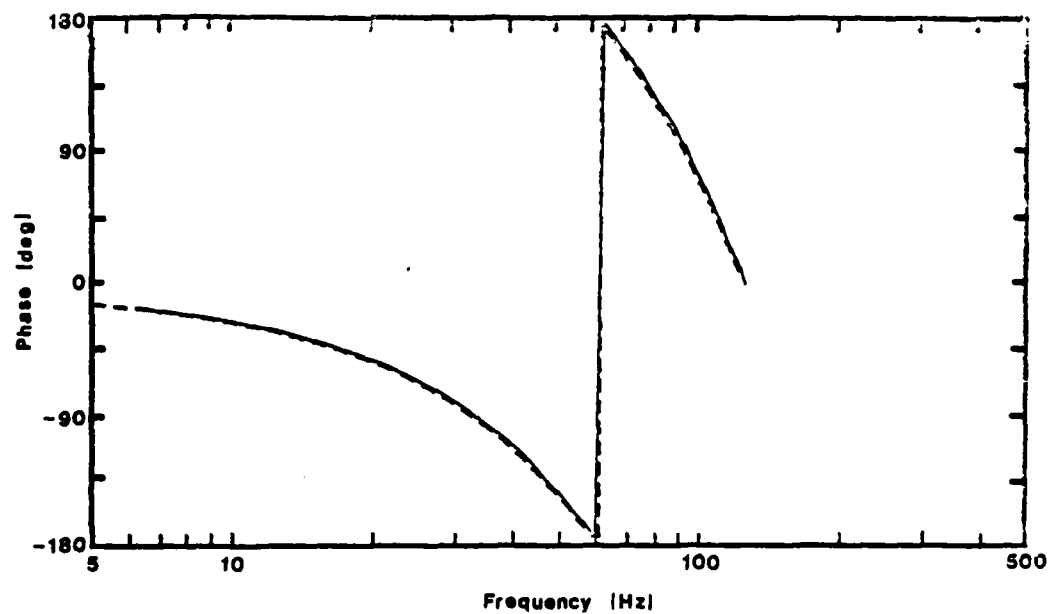
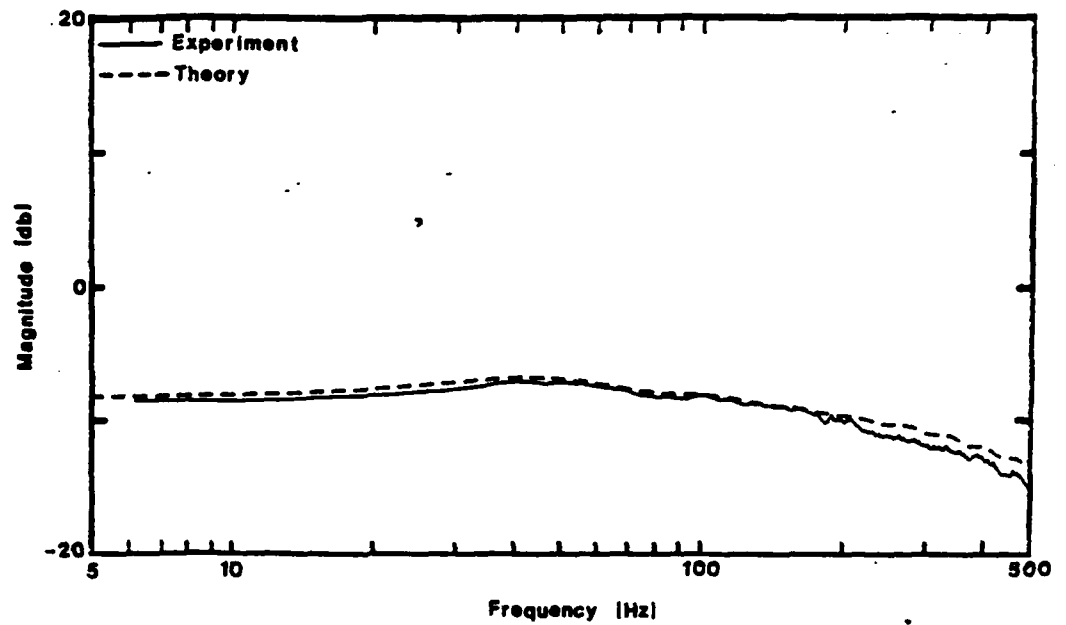
Data Set 75. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



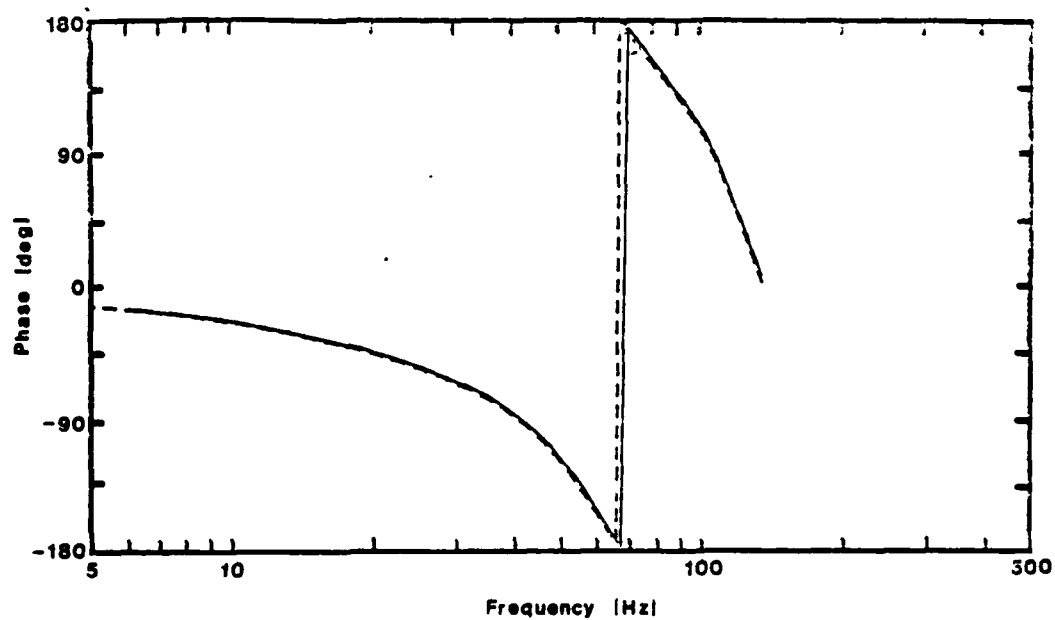
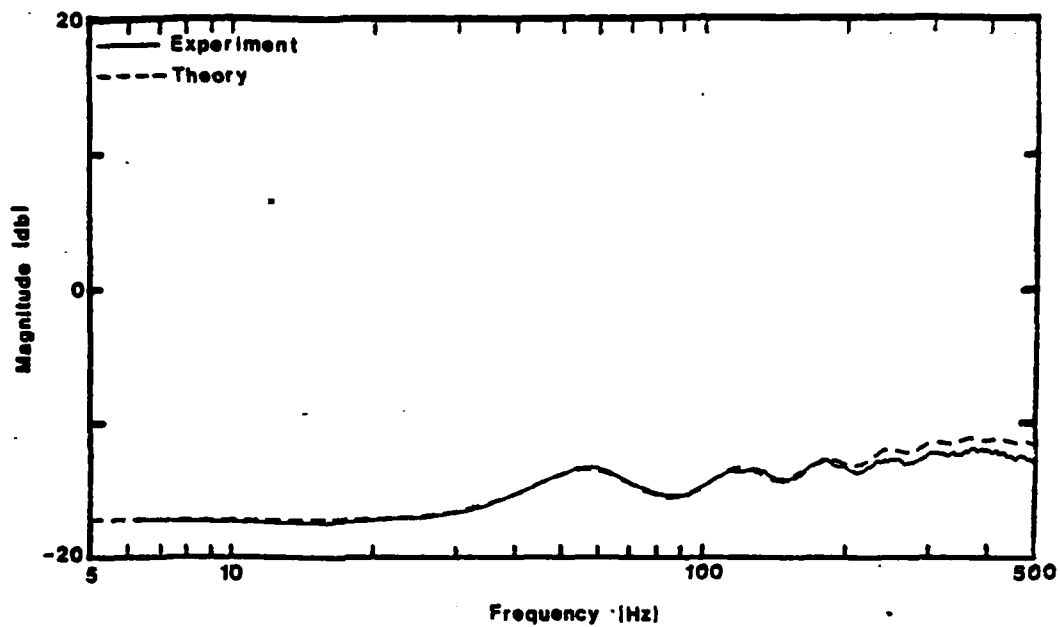
Data Set 76. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



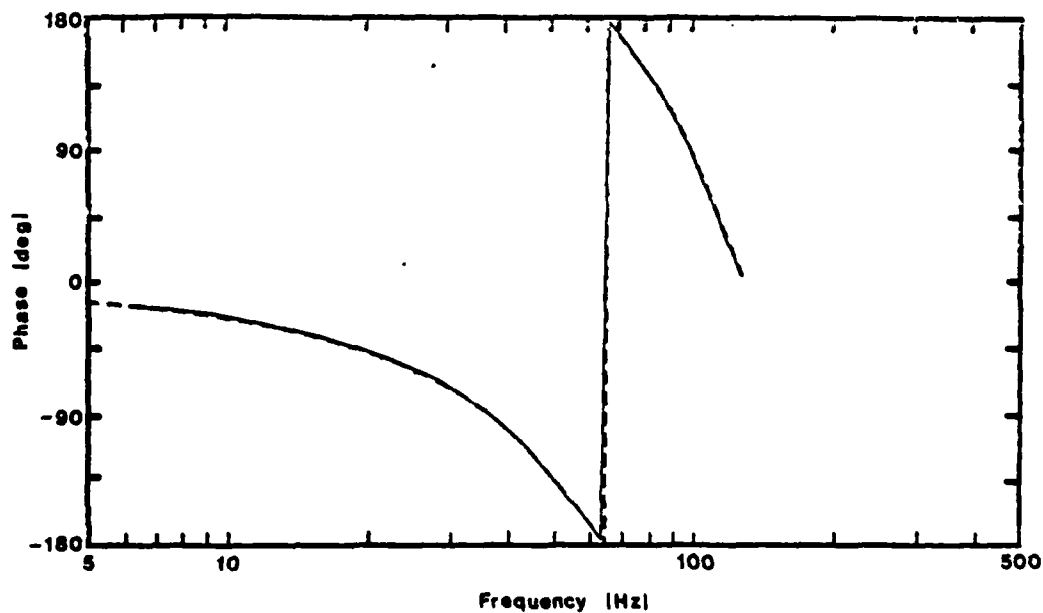
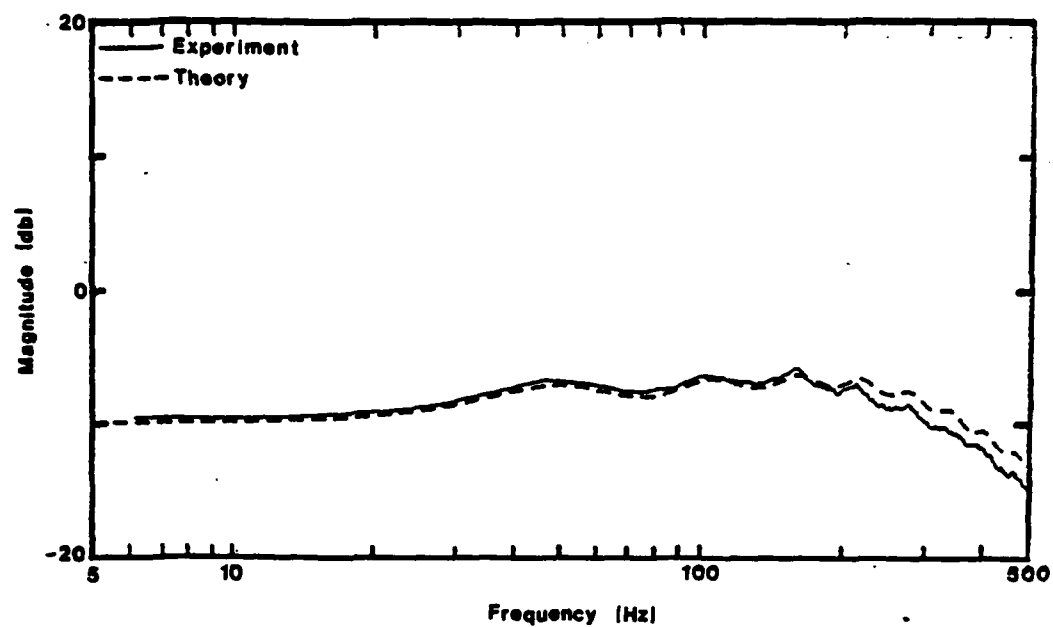
Data Set 77. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



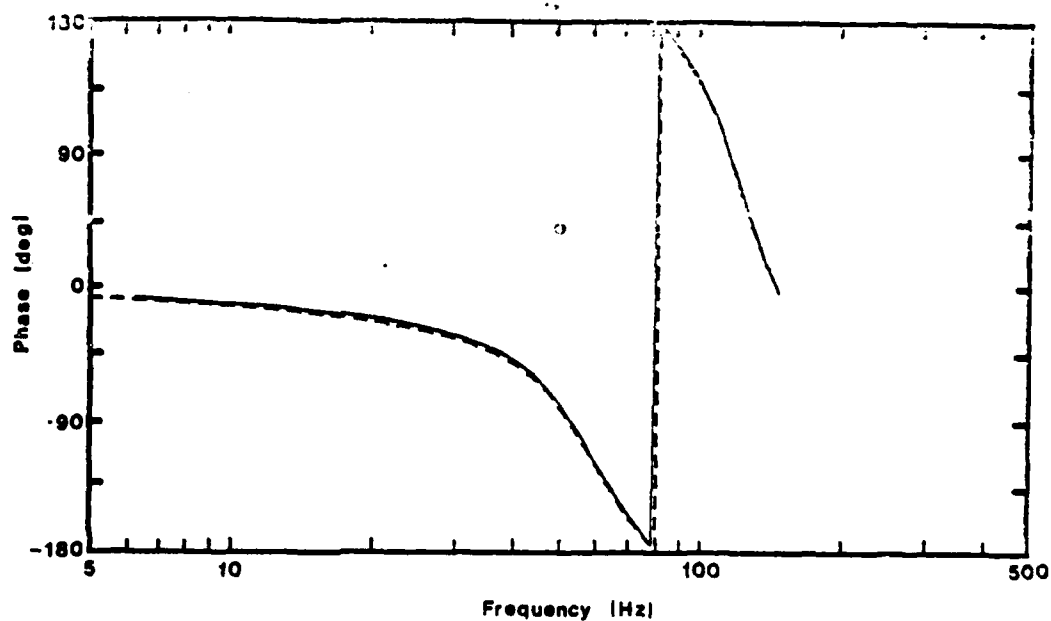
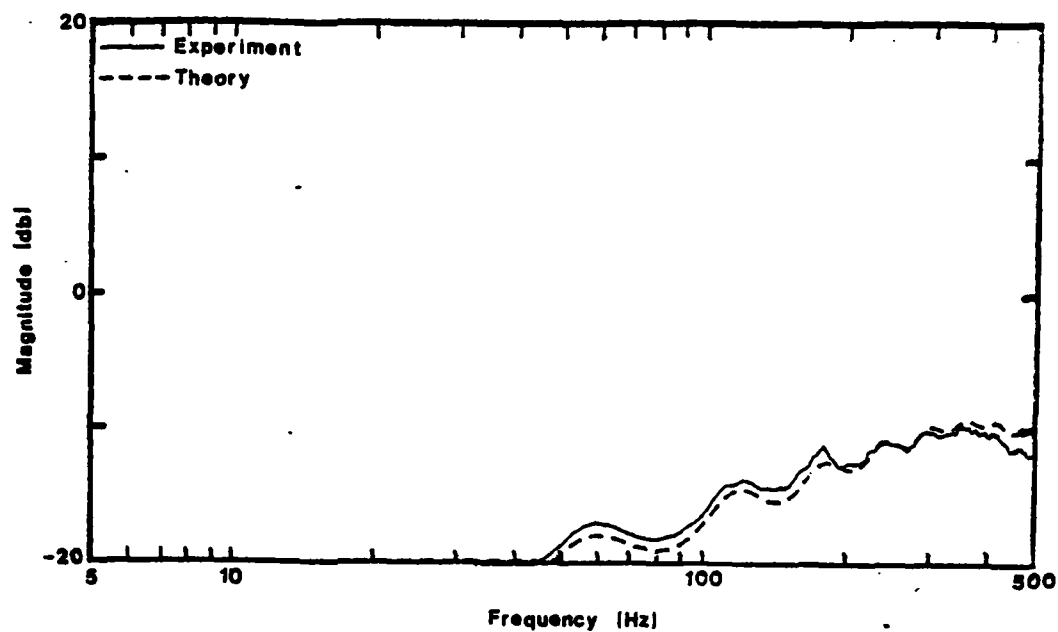
Data Set 78. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



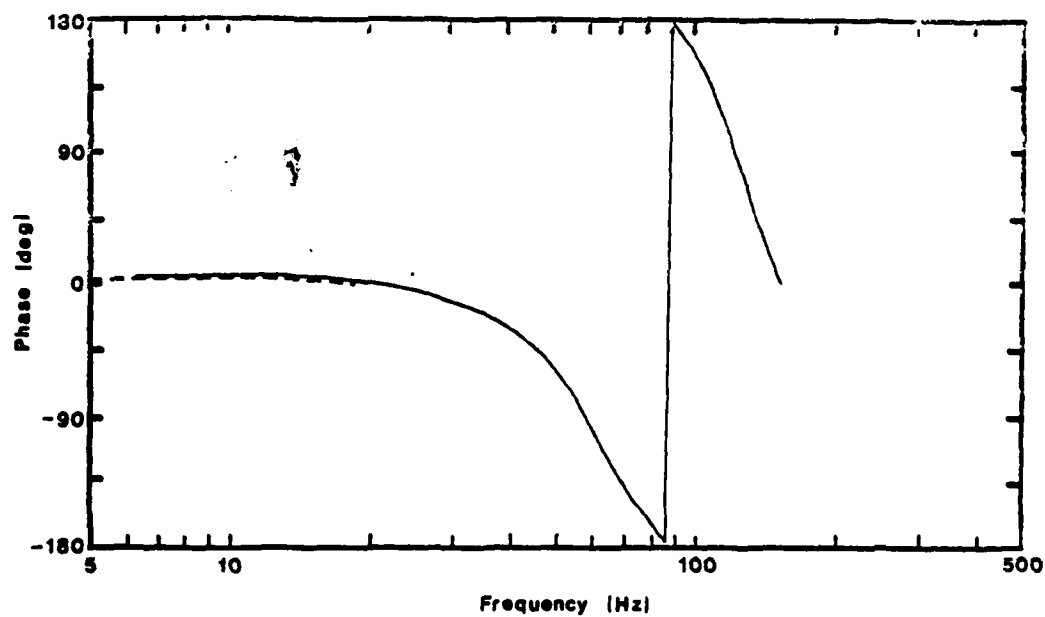
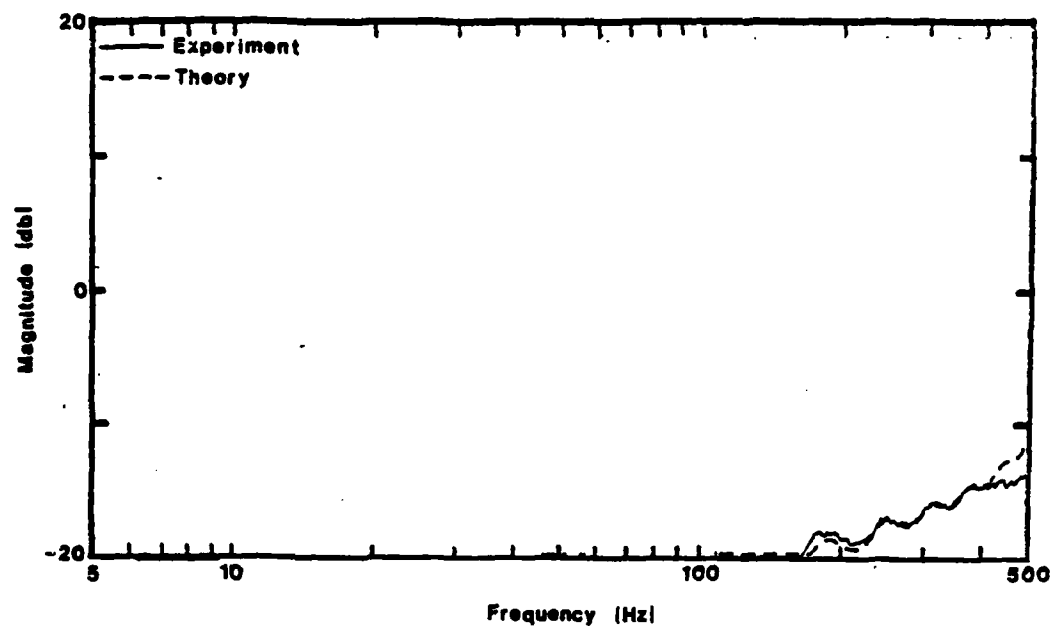
Data Set 79. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: #4,  $\ell = 50$  mm,  $d = .716$  mm)



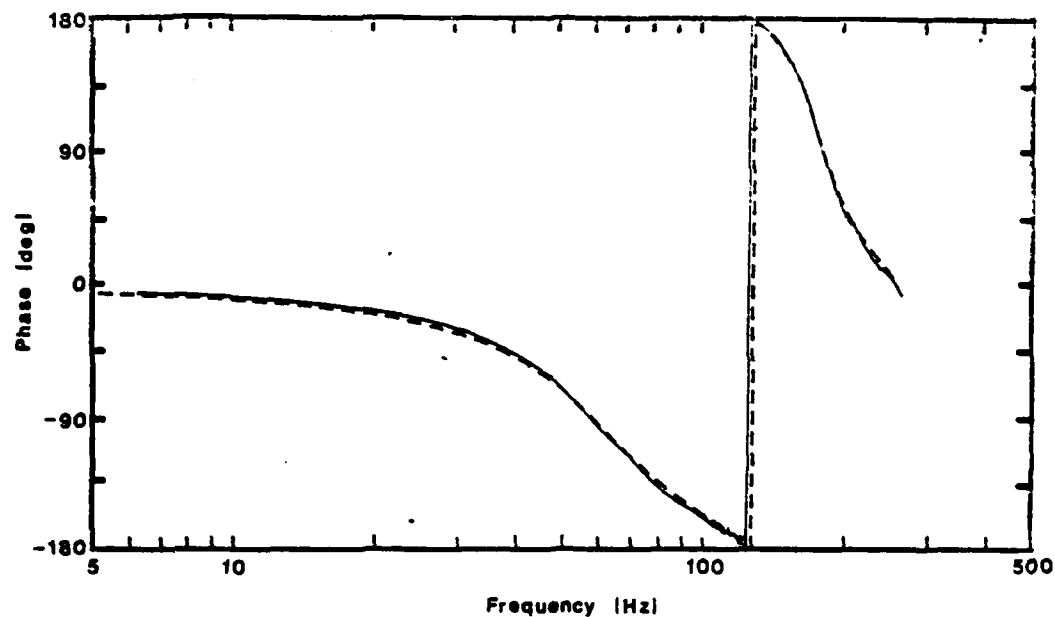
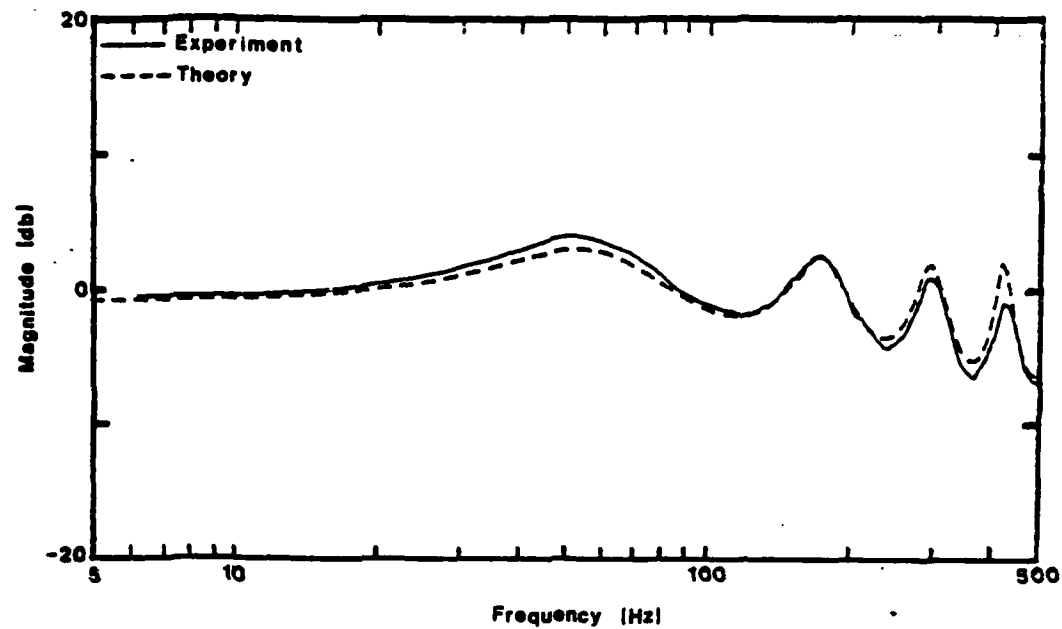
Data Set 80. Line with Source Impedance and Load Impedance  
( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



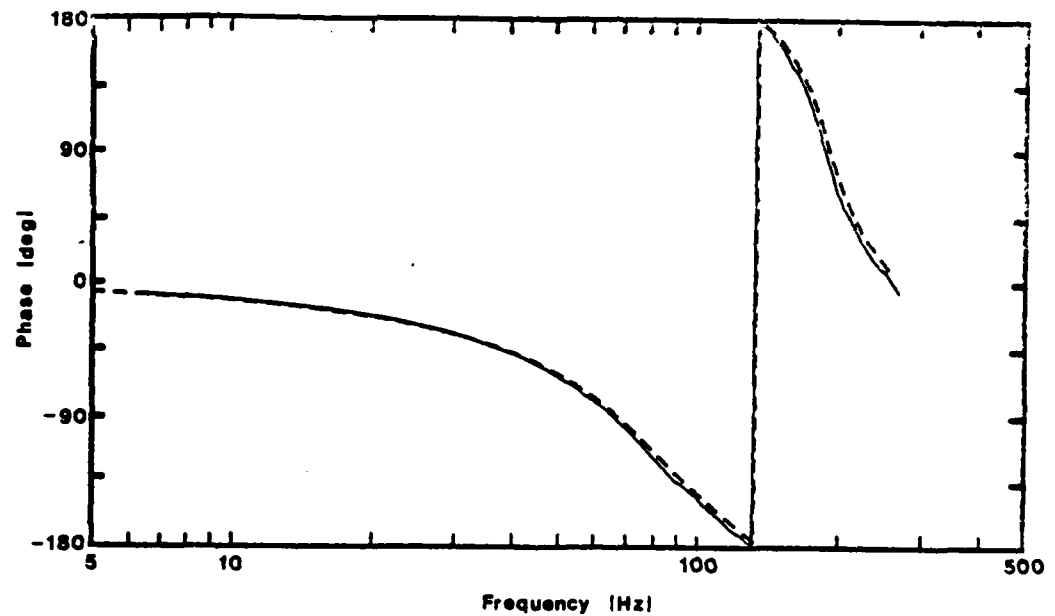
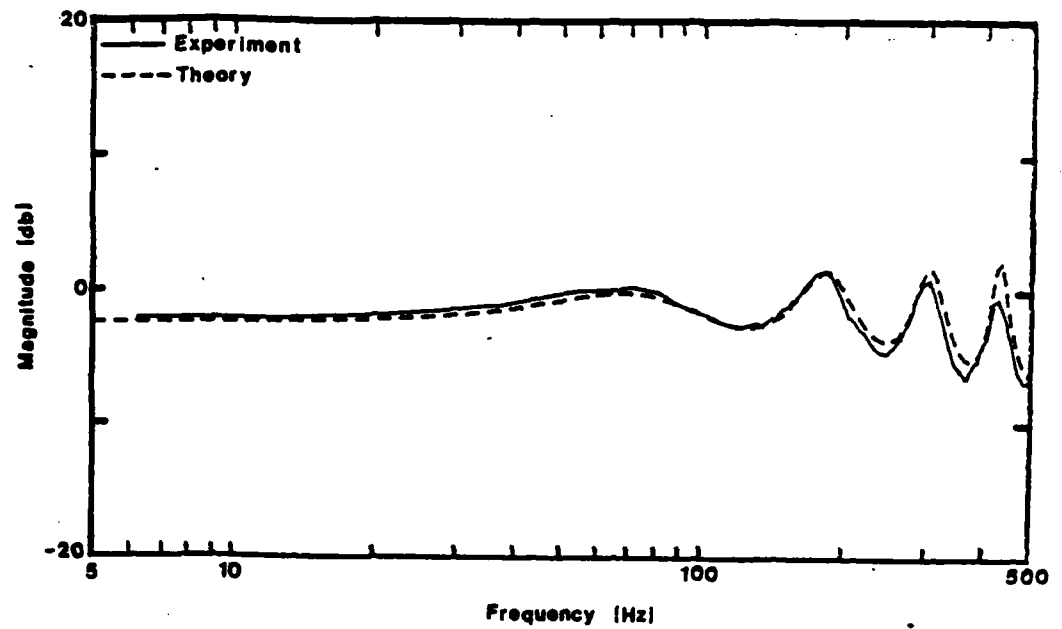
Data Set 81. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



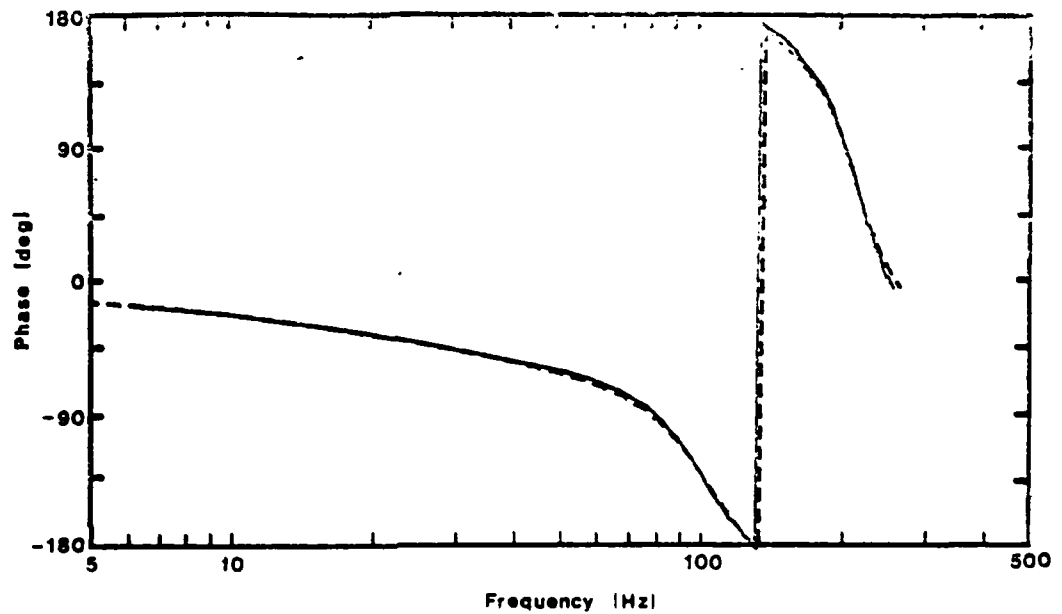
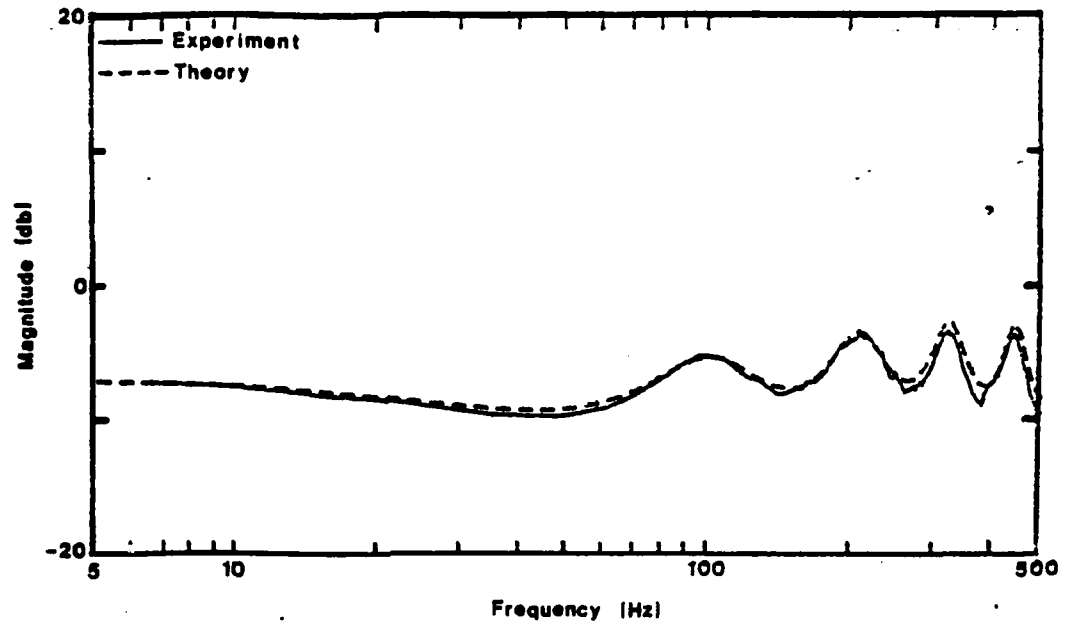
Data Set 82. Line with Source Impedance and Load Impedance  
( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



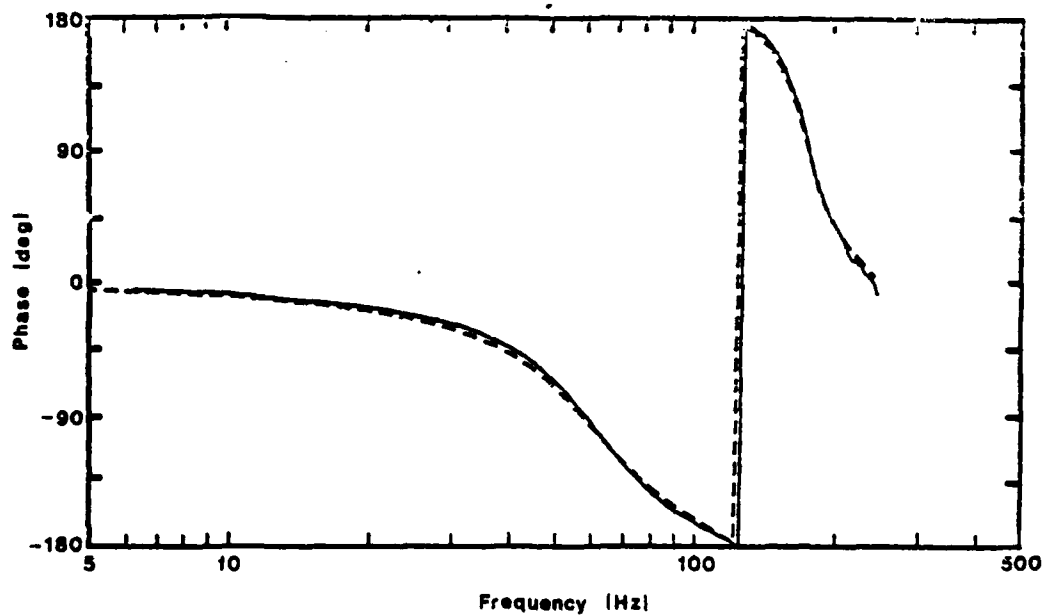
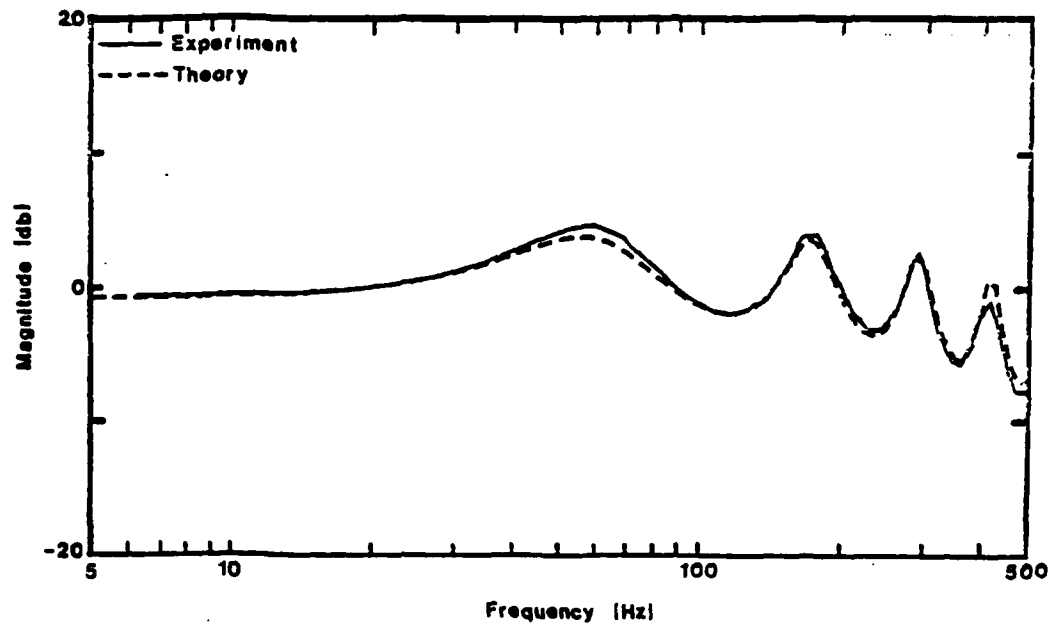
Data Set 83. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



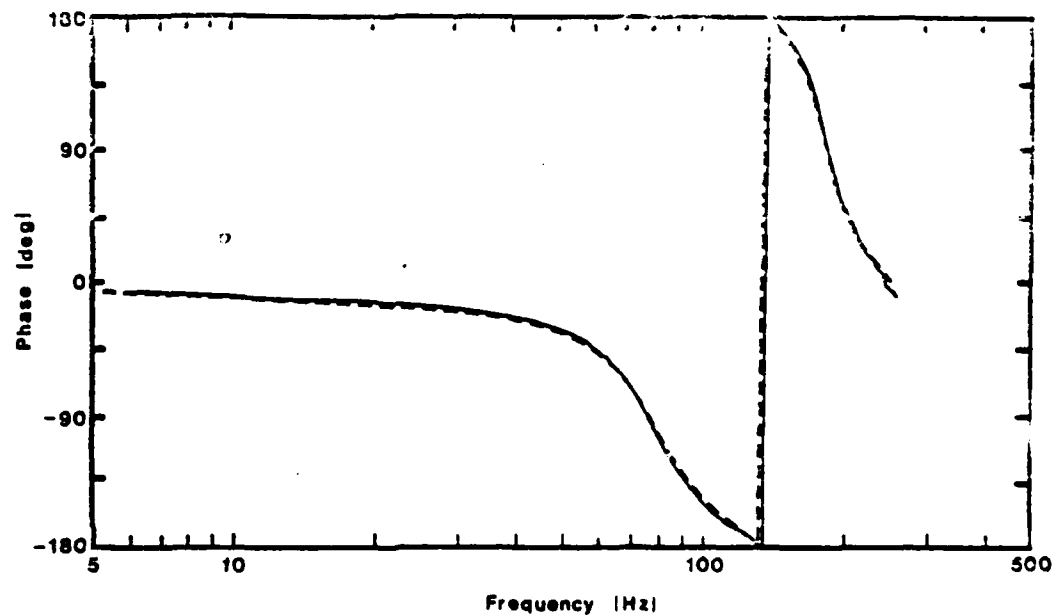
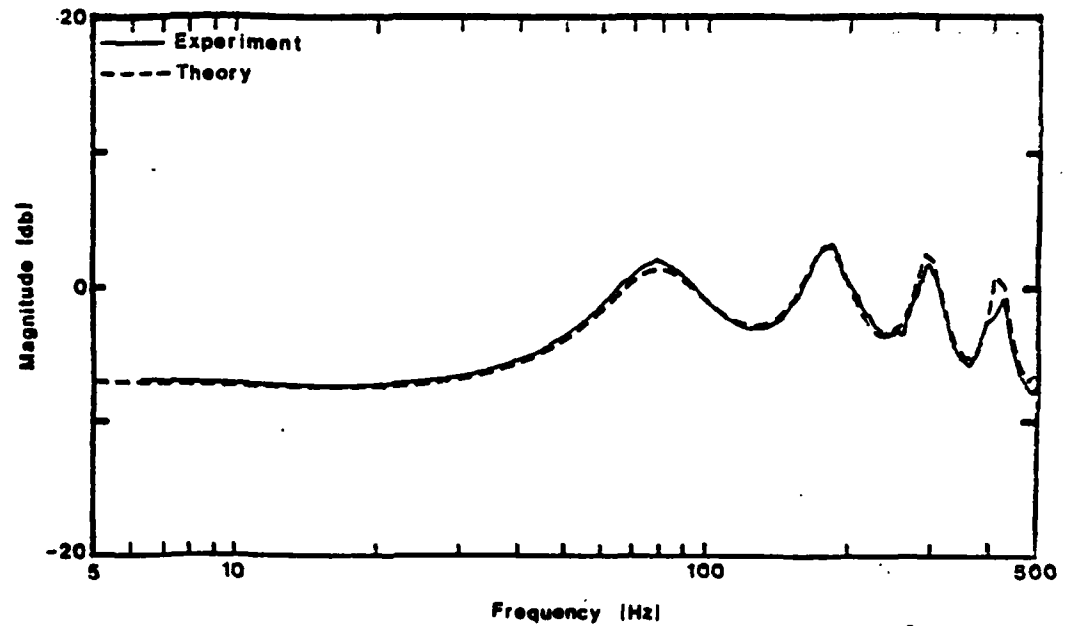
Data Set 84. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$ ,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



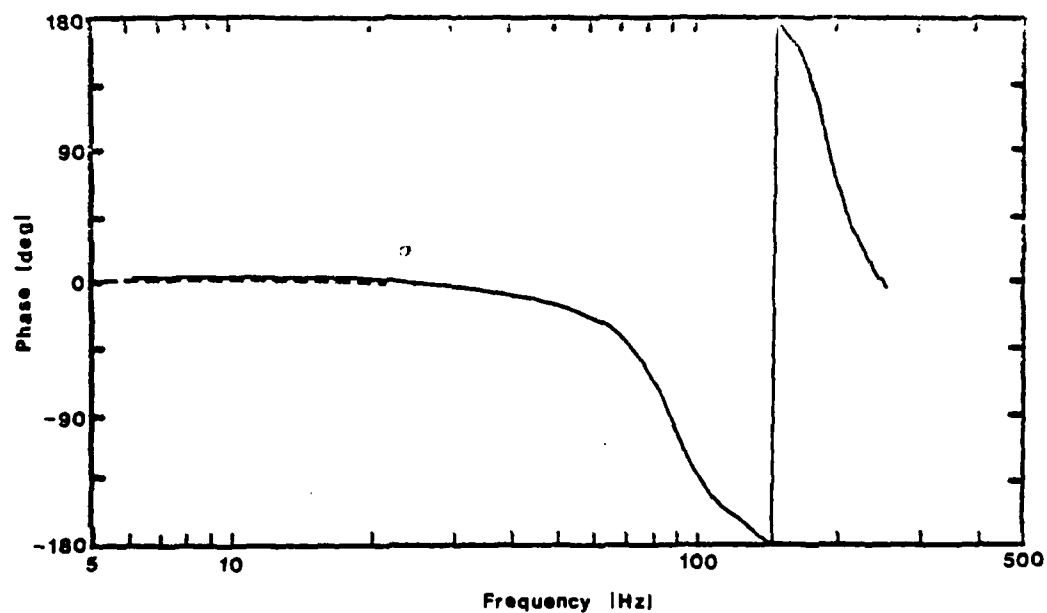
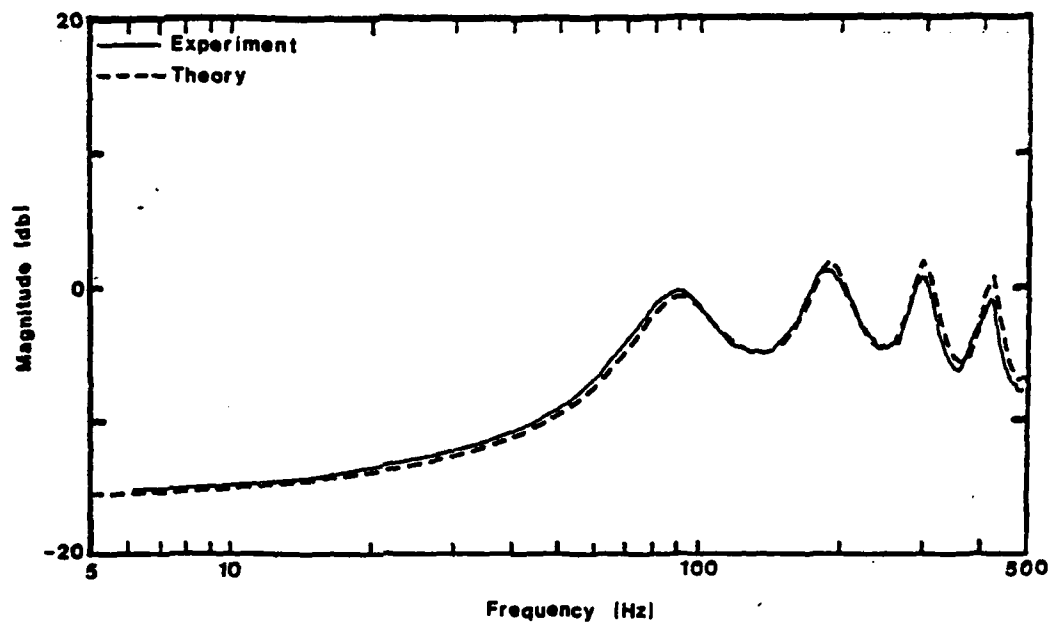
Data Set 85. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$ ,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



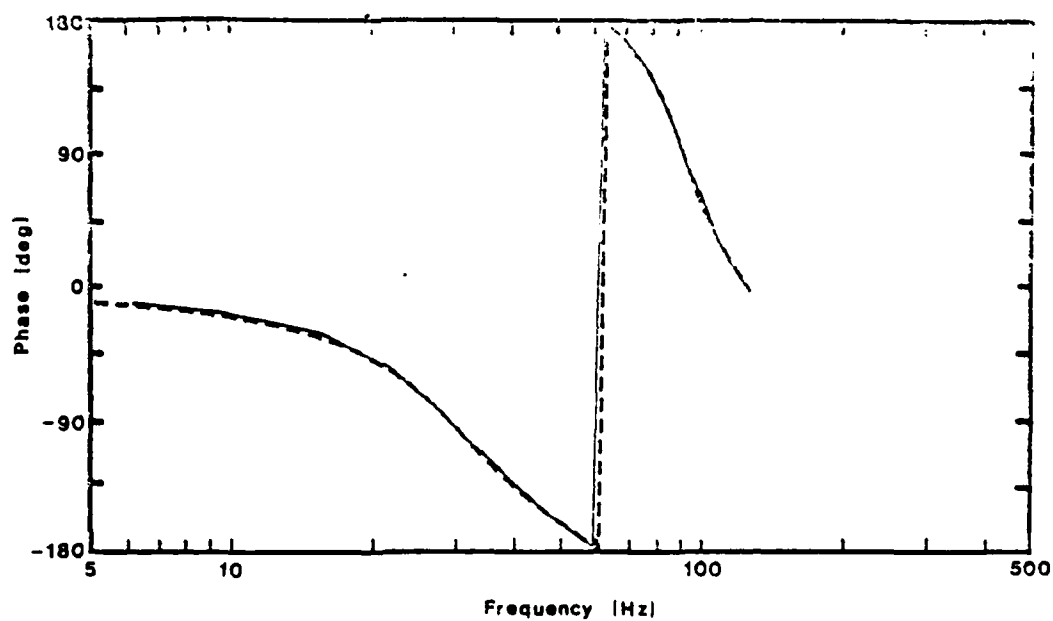
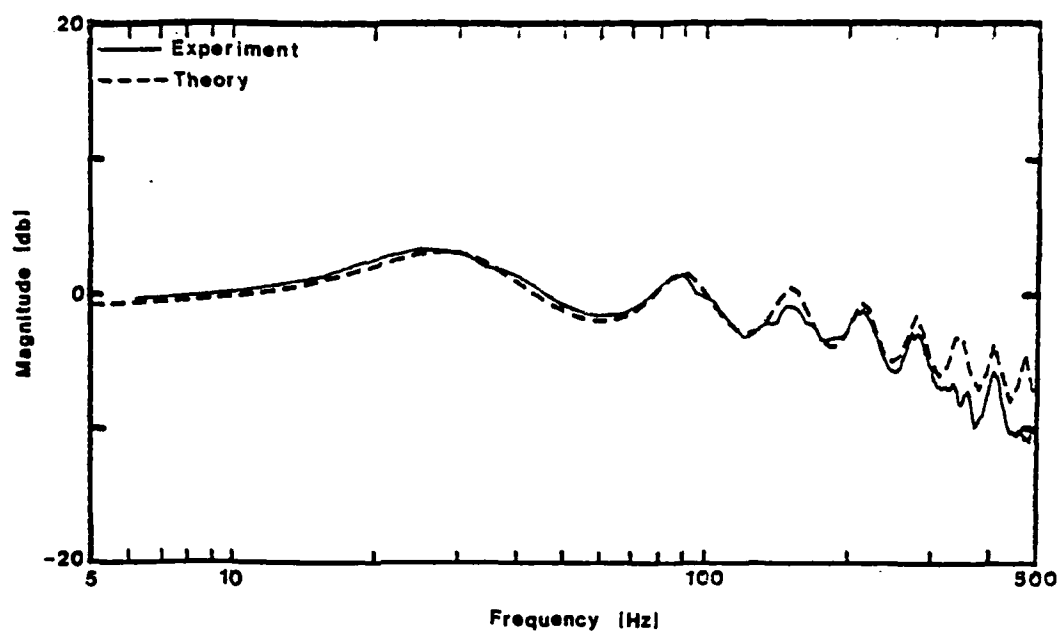
Data Set 86. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$ ,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



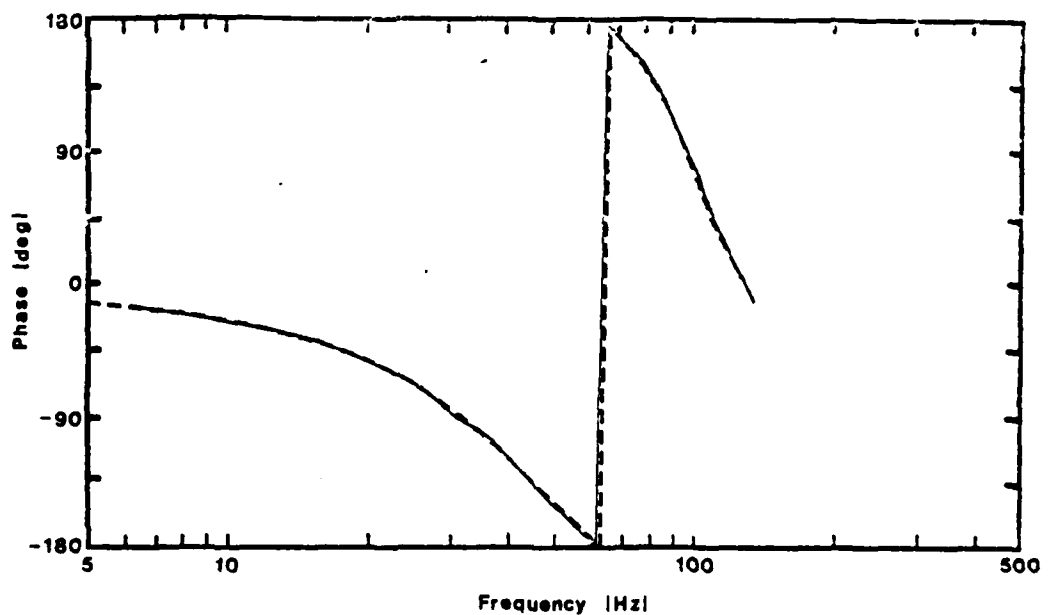
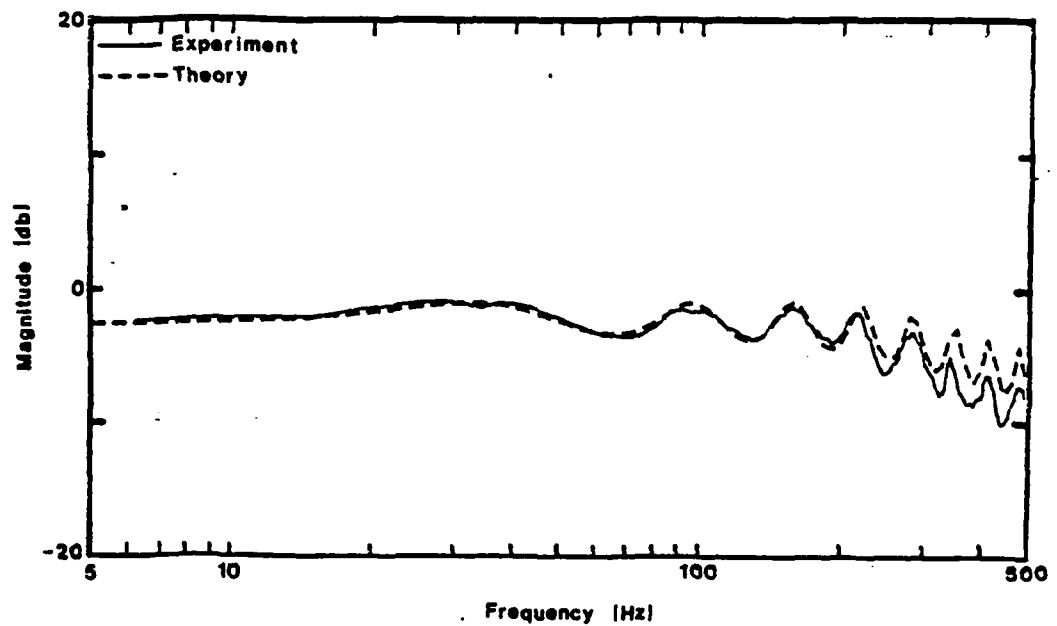
Data Set 87. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$ ,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



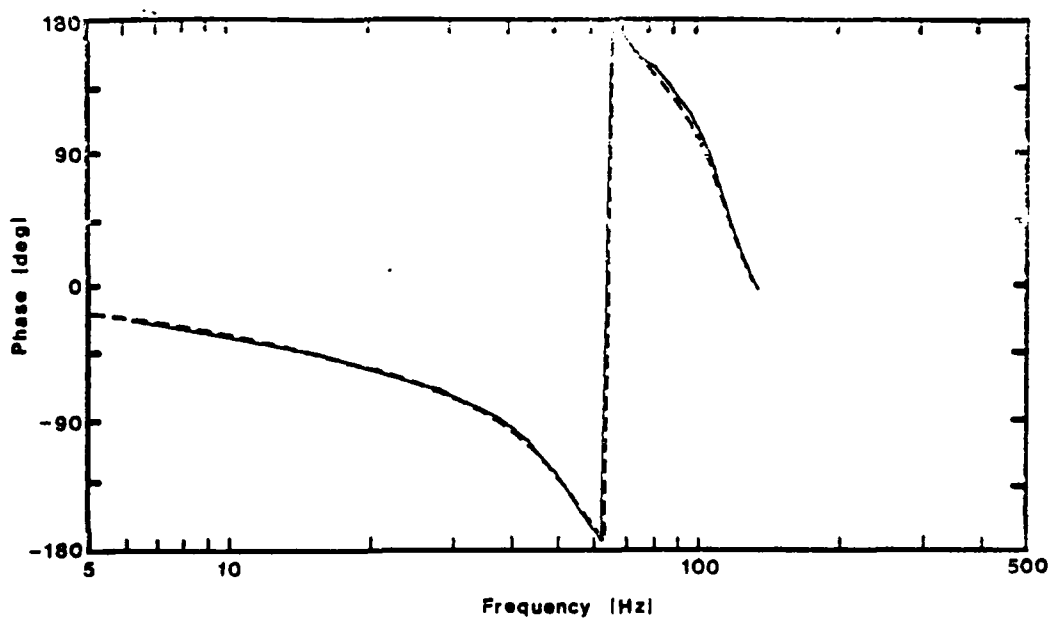
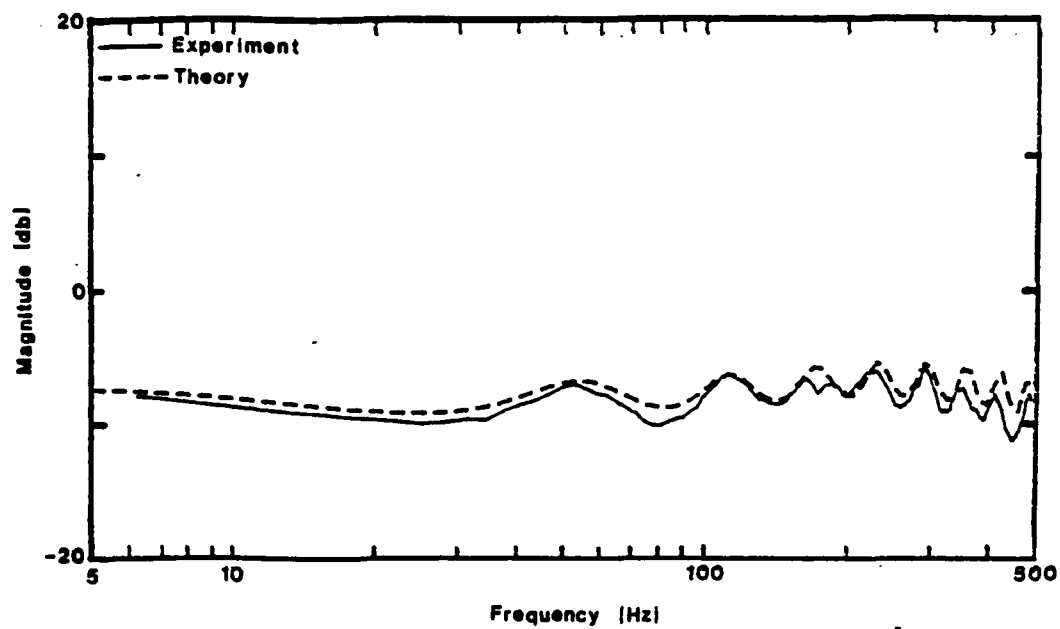
Data Set 88. Line with Source Impedance and Load Impedance  
( $\ell = 4.8$ ,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



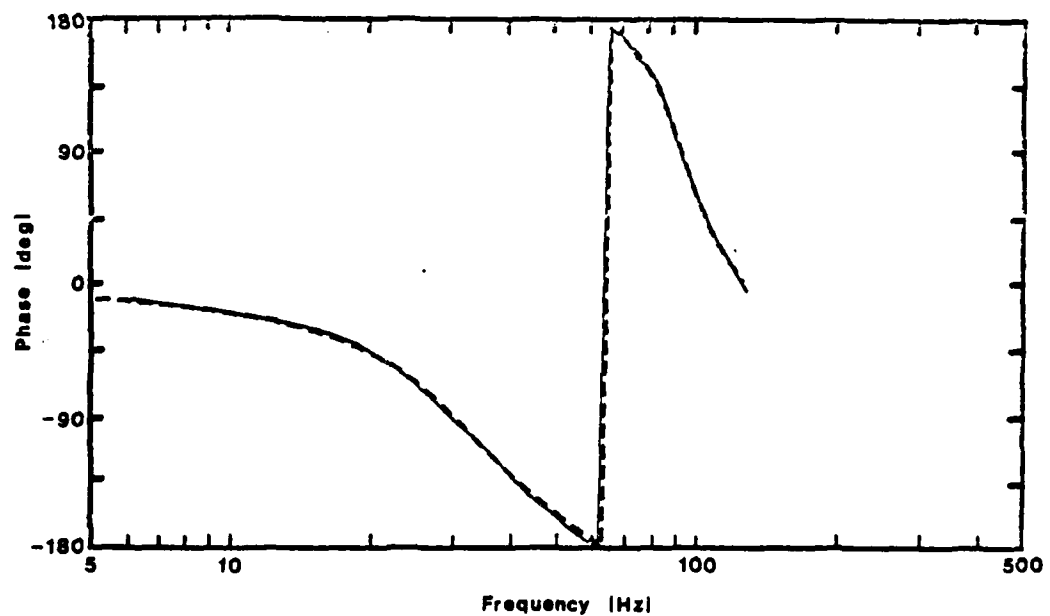
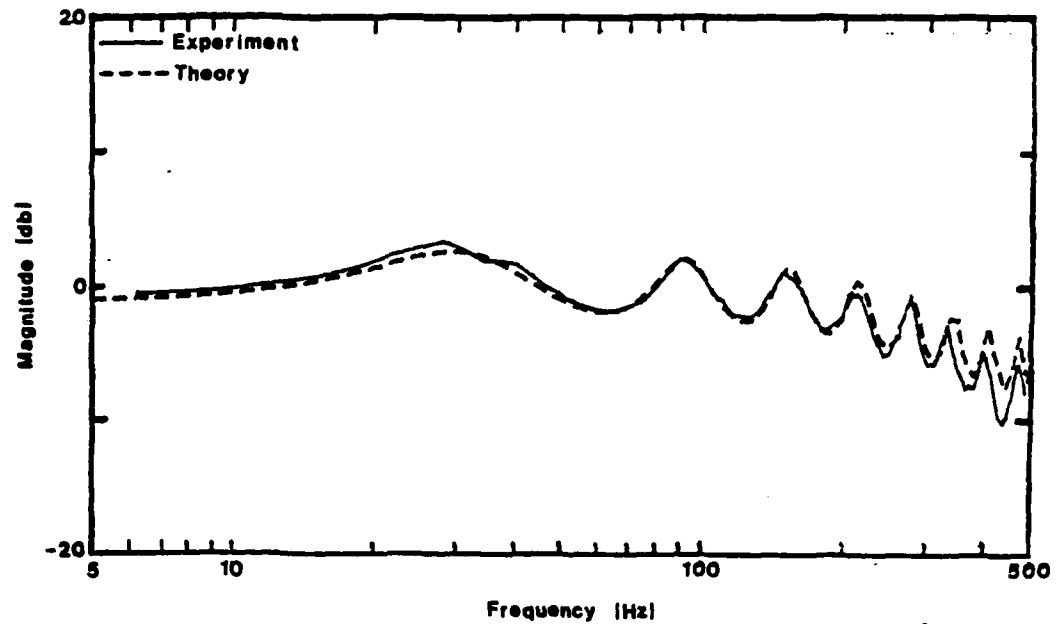
Data Set 89. Line with Source Impedance and Load Impedance  
( $\lambda = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



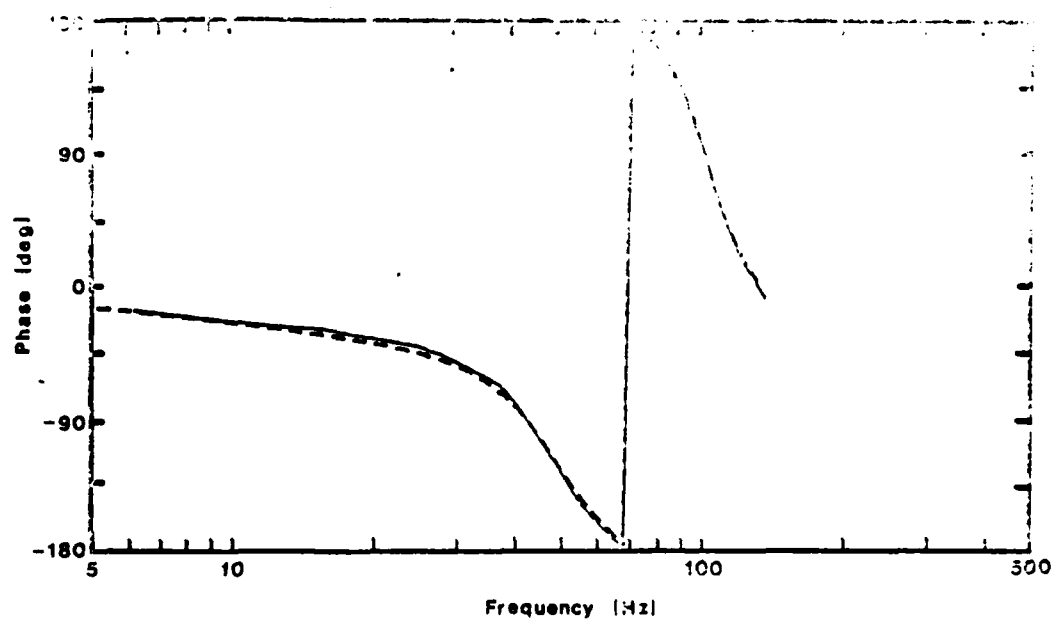
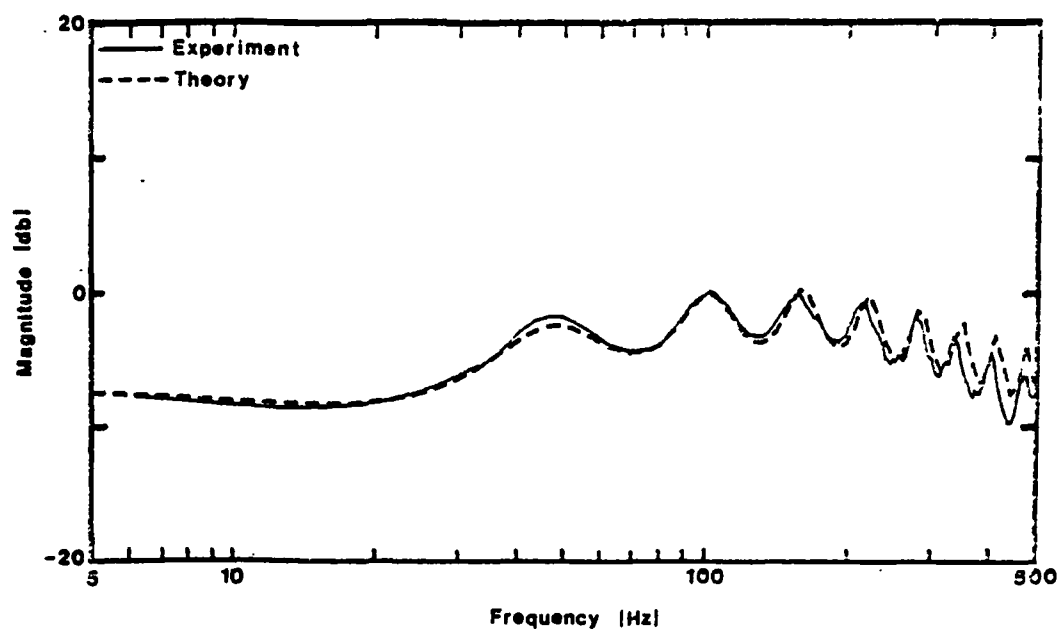
Data Set 90. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes.  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



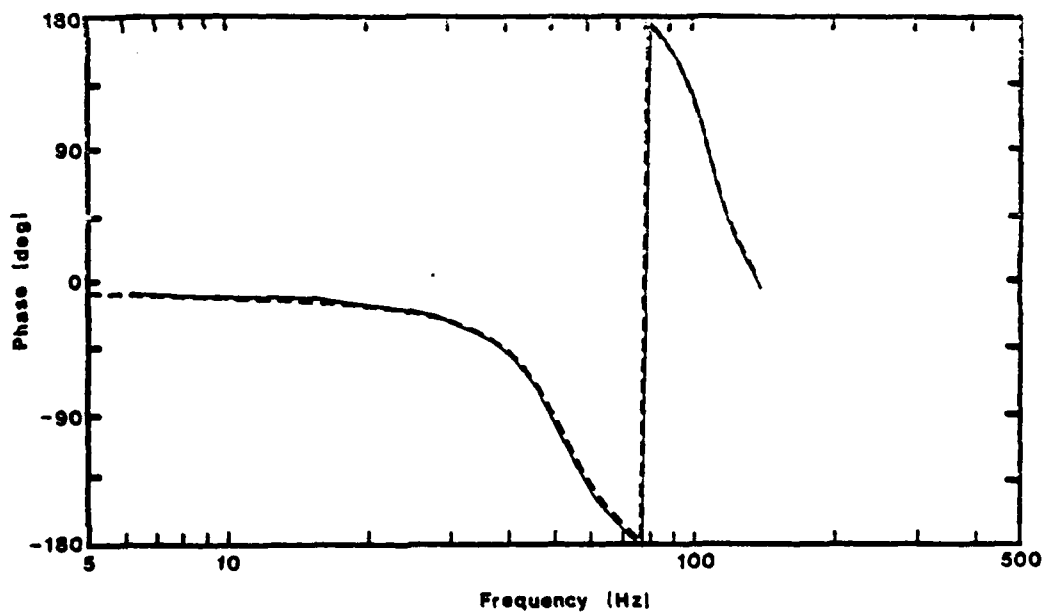
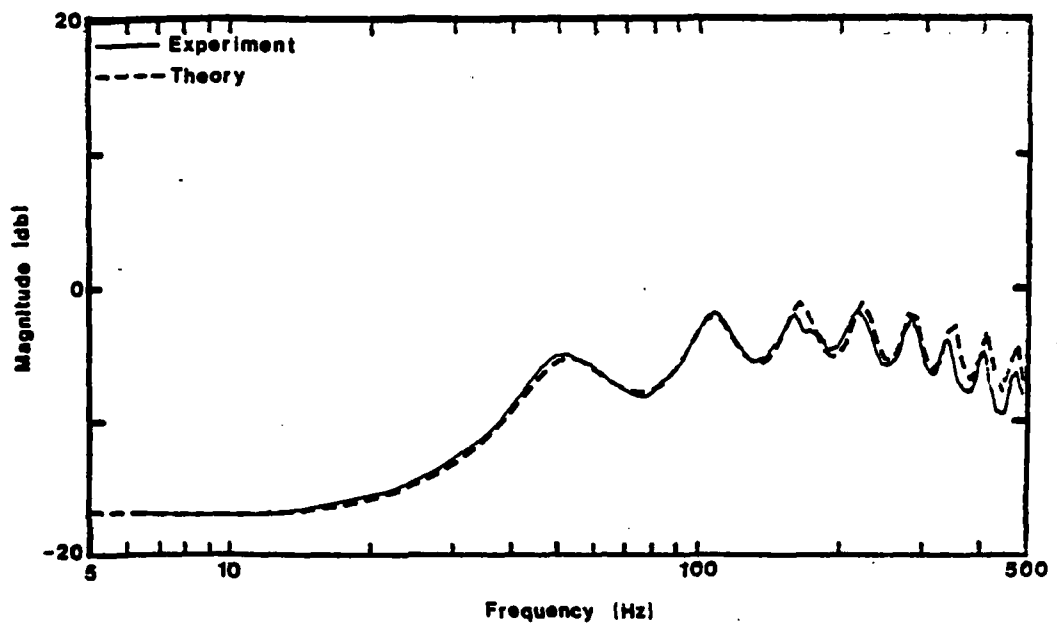
Data Set 91. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



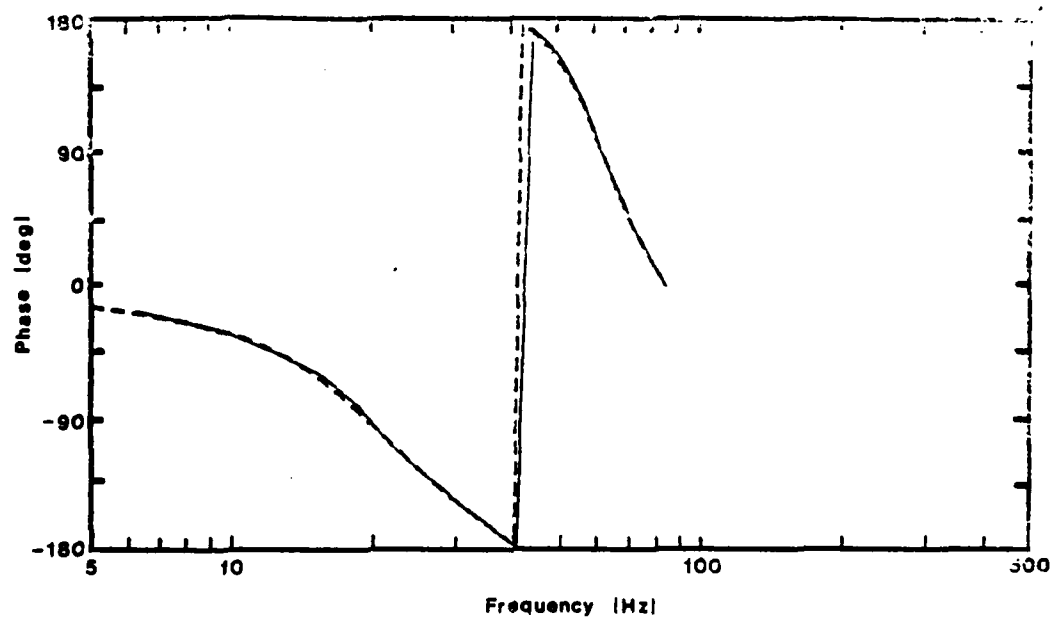
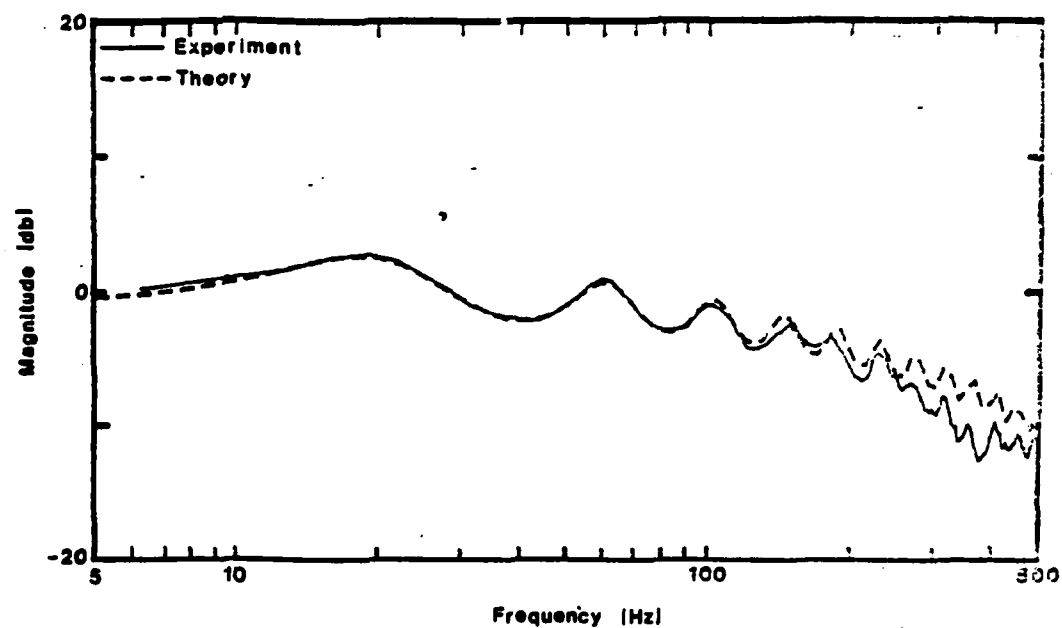
Data Set 92. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



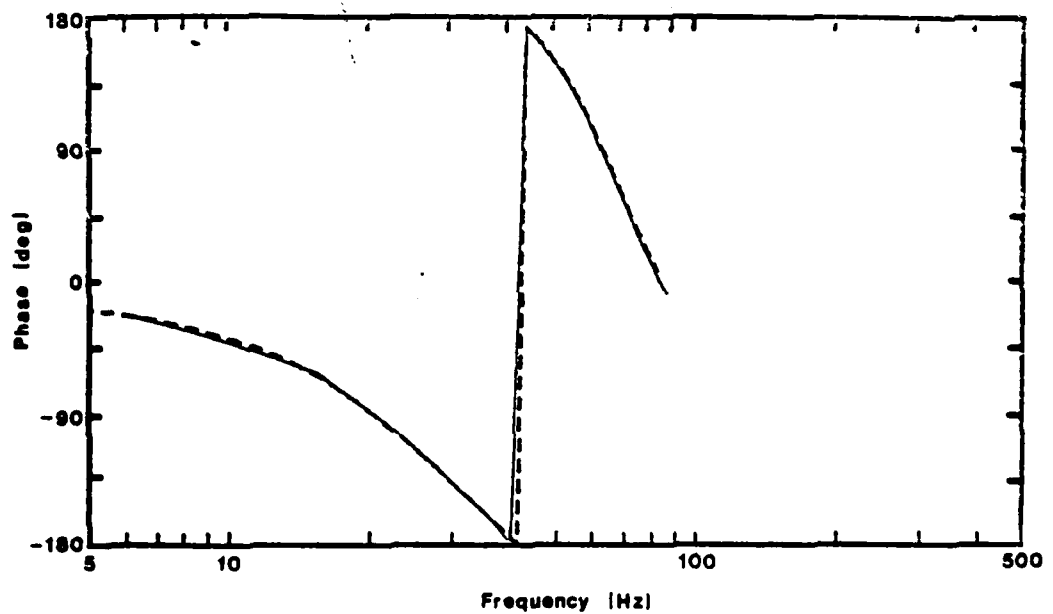
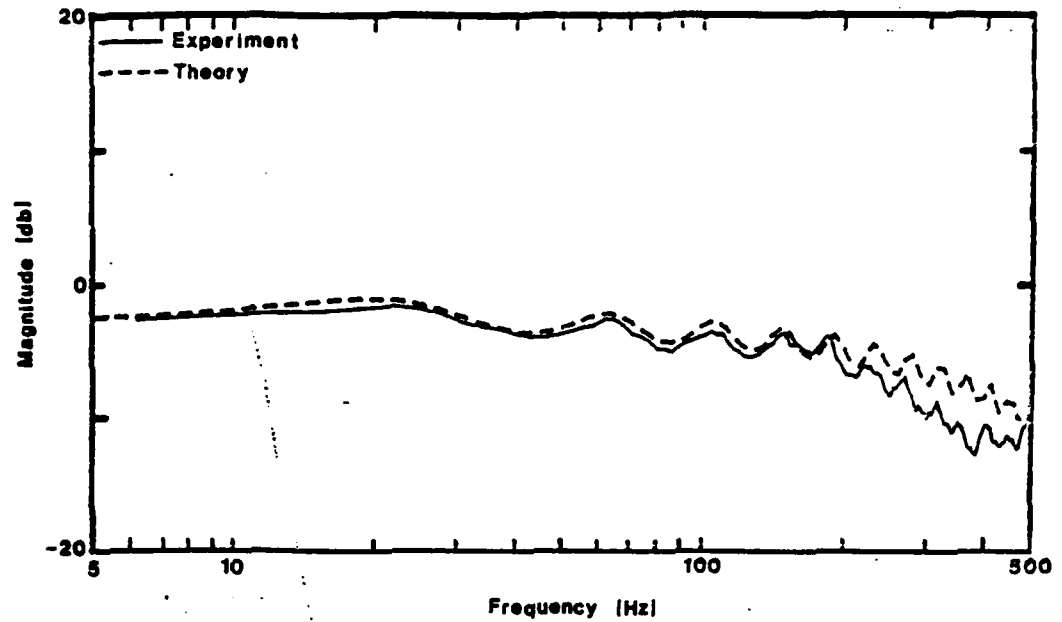
Data Set 93. Line with Source Impedance and Load Impedance  
( $\lambda = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\lambda = 290$  mm,  $d = 1.63$  mm)



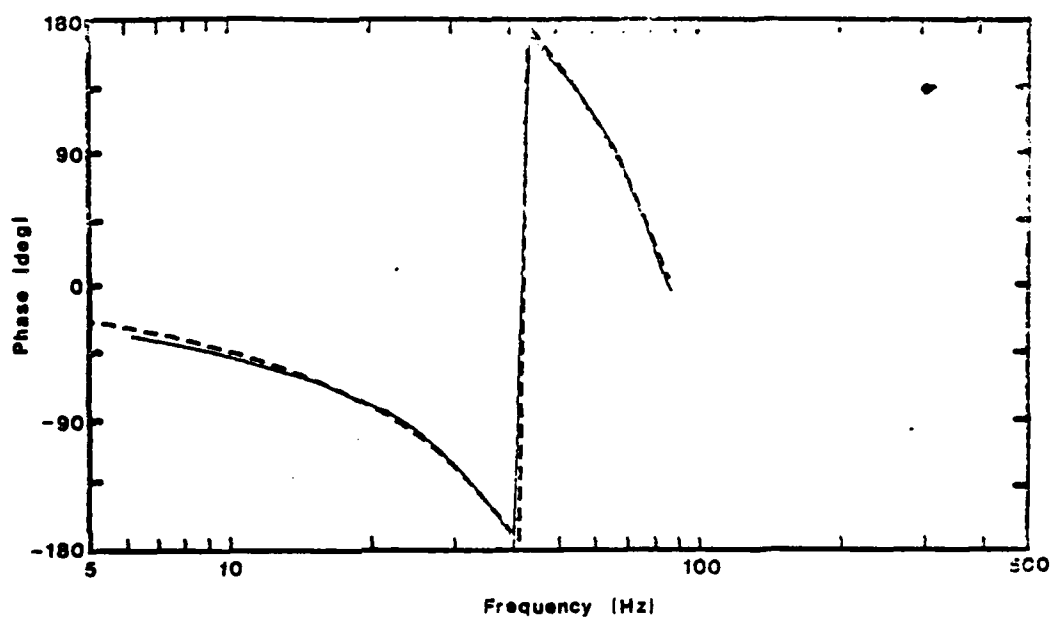
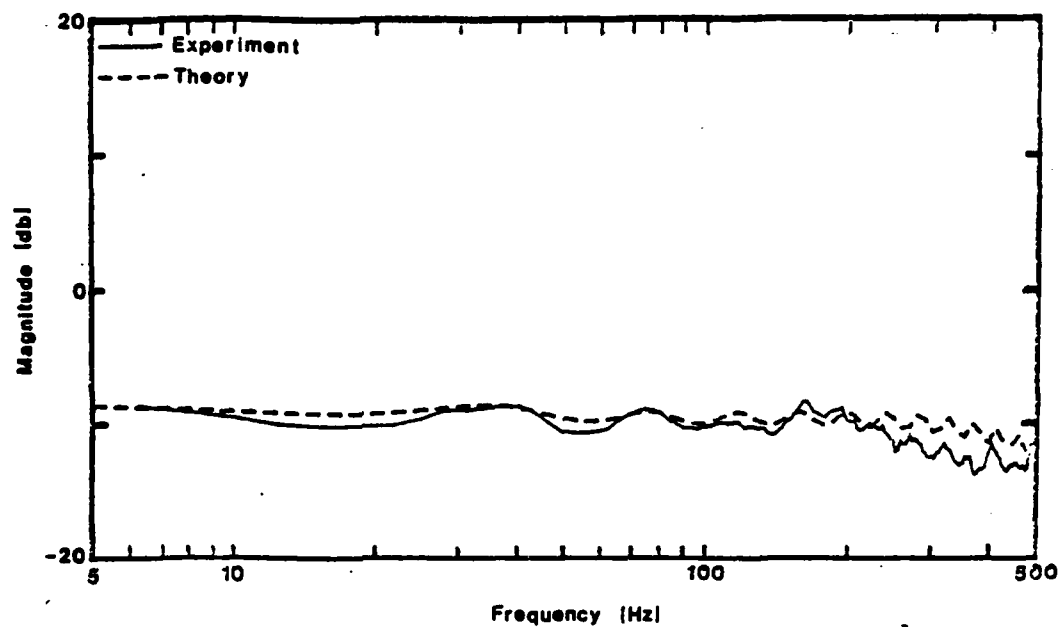
Data Set 94. Line with Source Impedance and Load Impedance  
( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



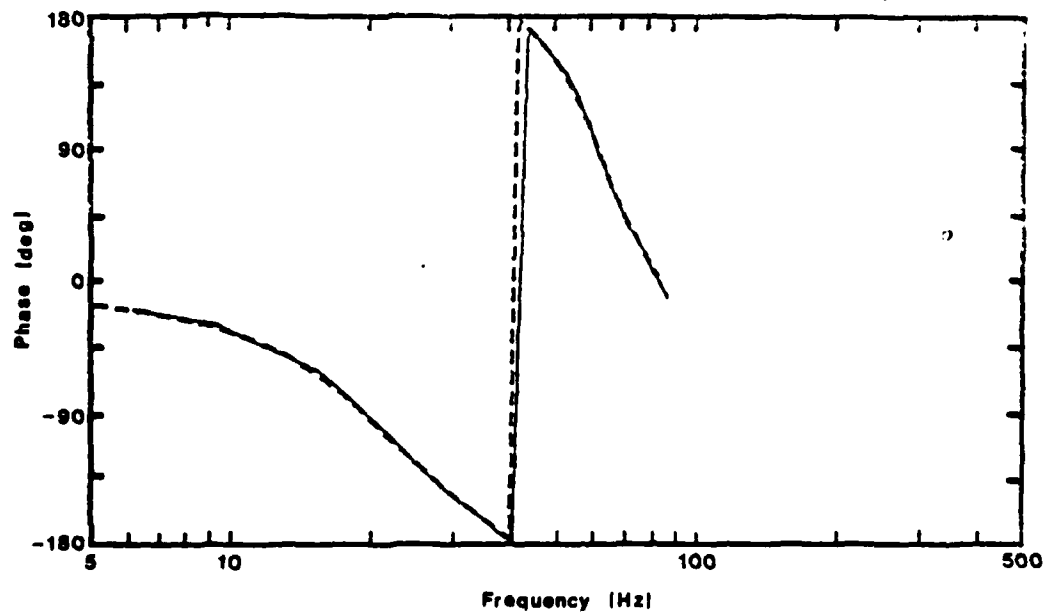
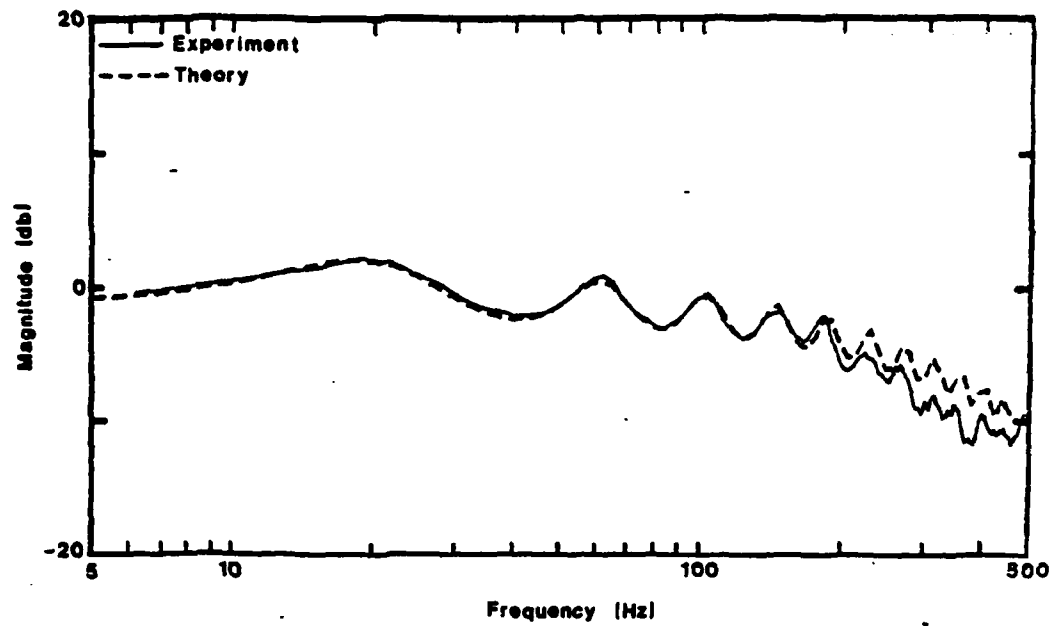
Data Set 95. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



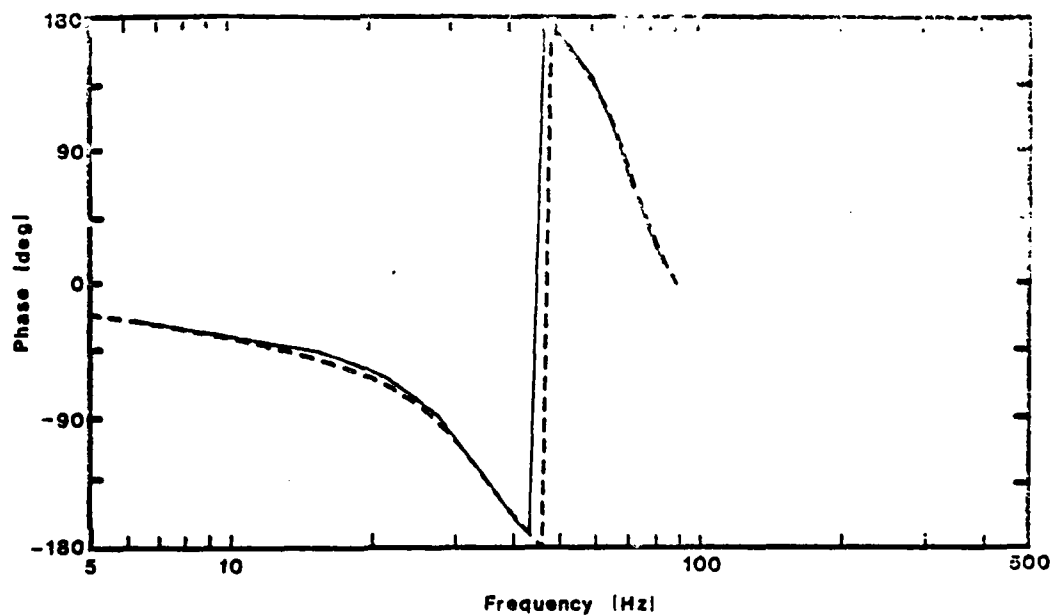
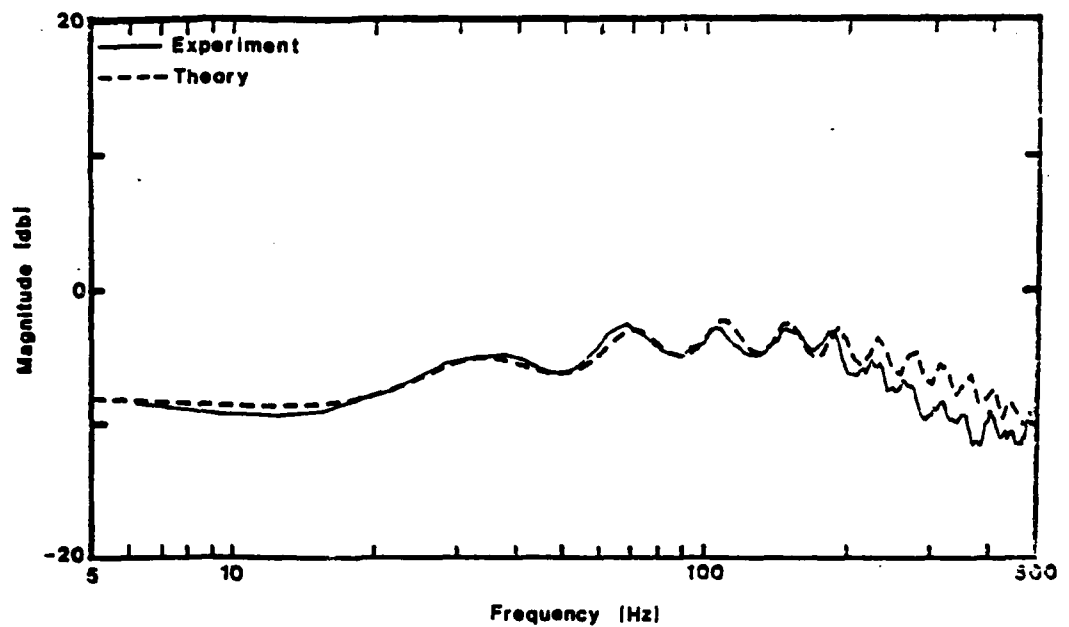
Data Set 96. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



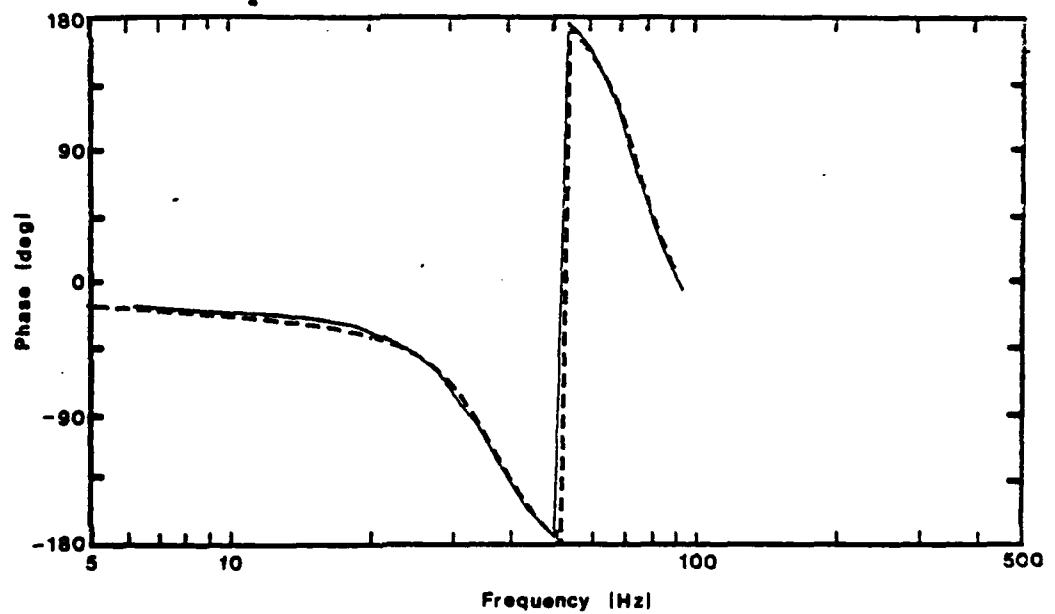
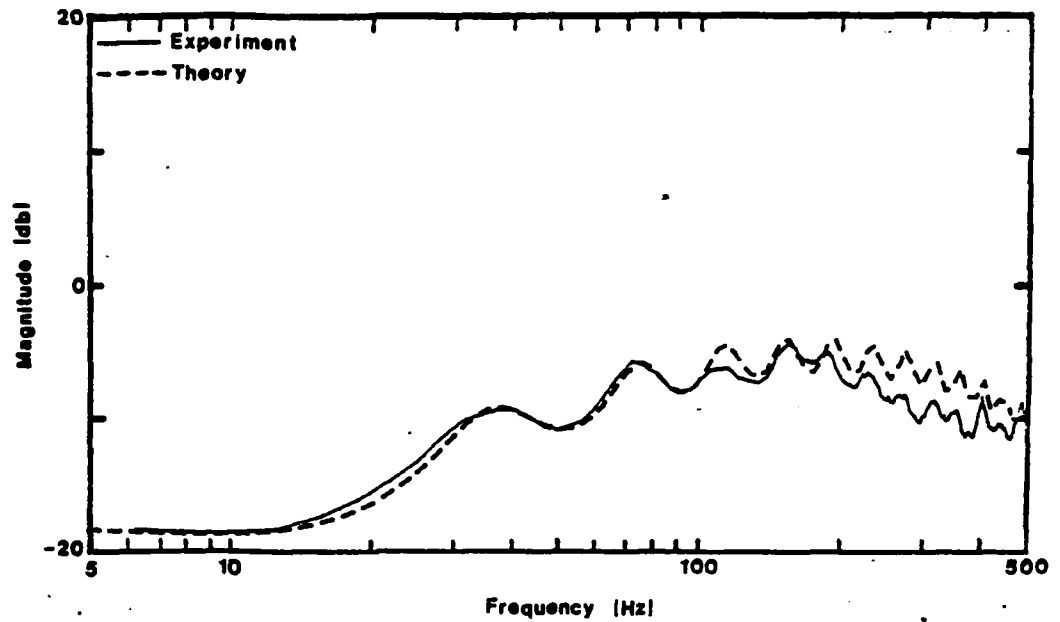
Data Set 97. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



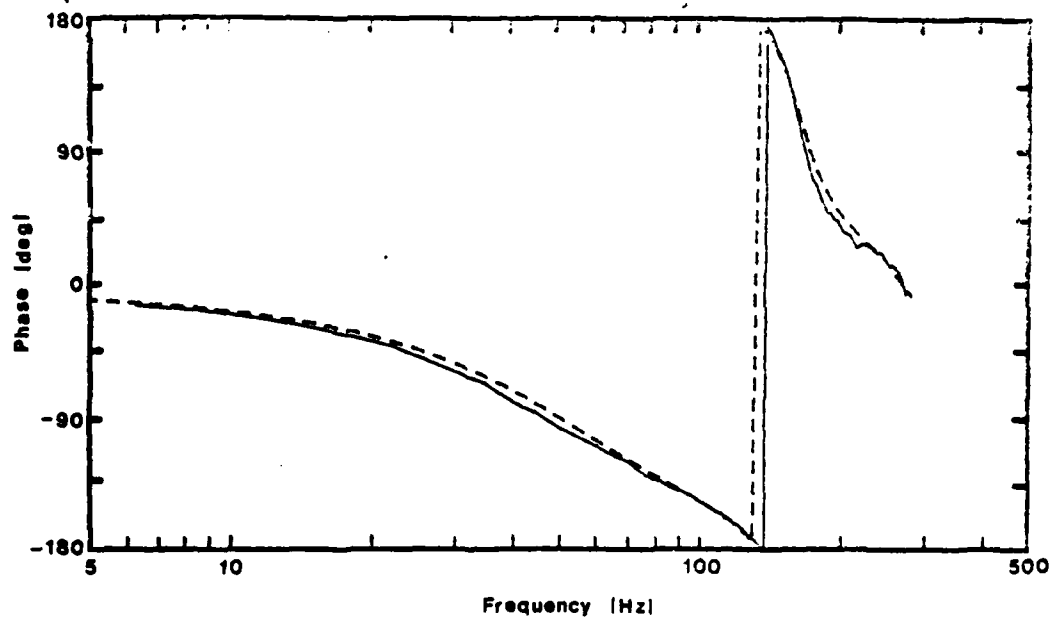
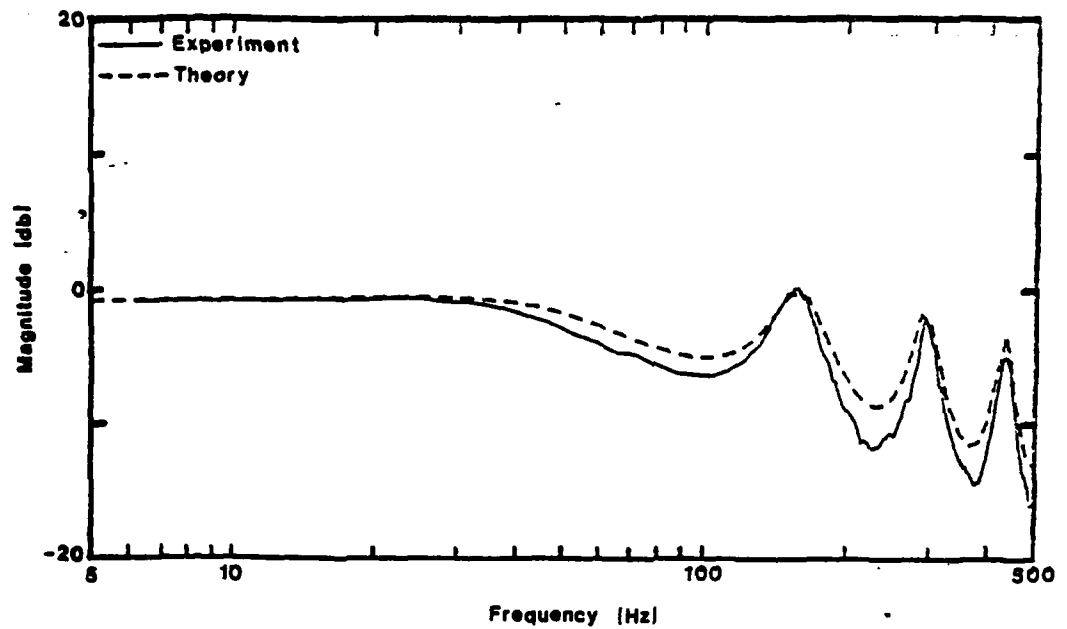
Data Set 98. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



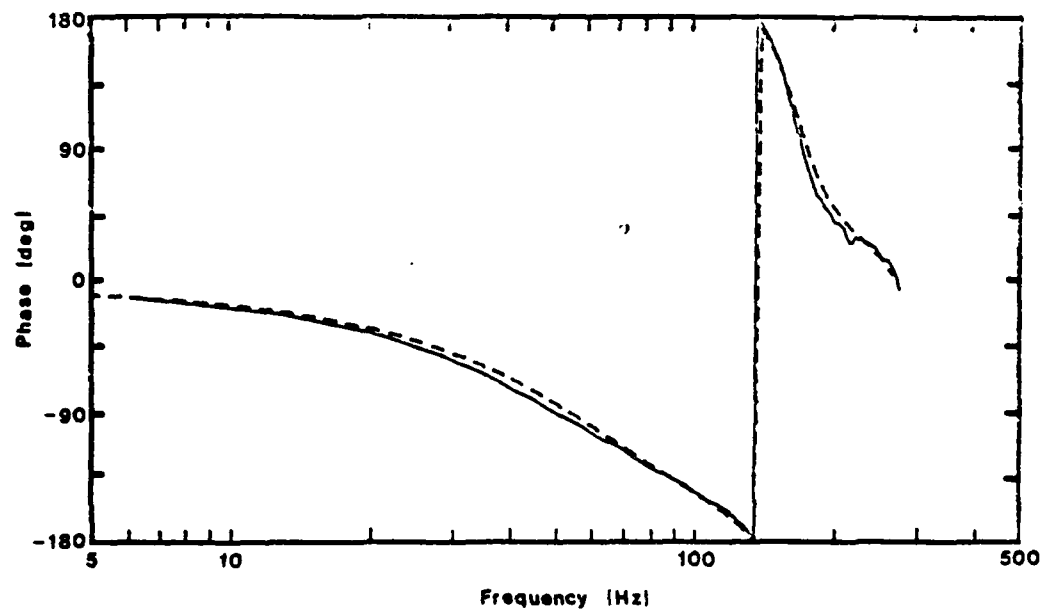
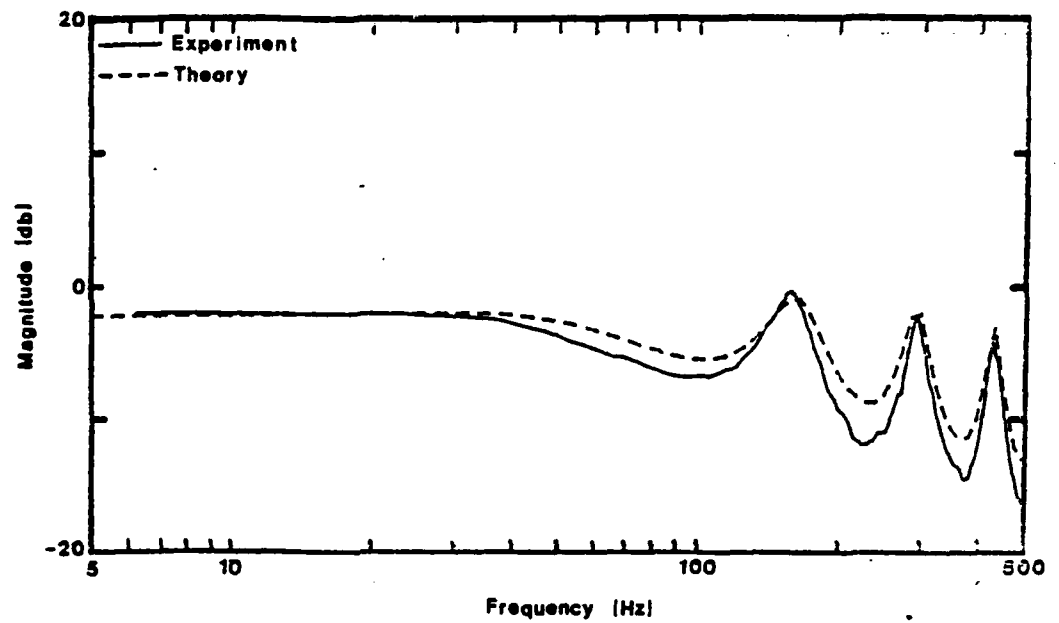
Data Set 99. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\lambda = 290$  mm,  $d = 1.63$  mm)



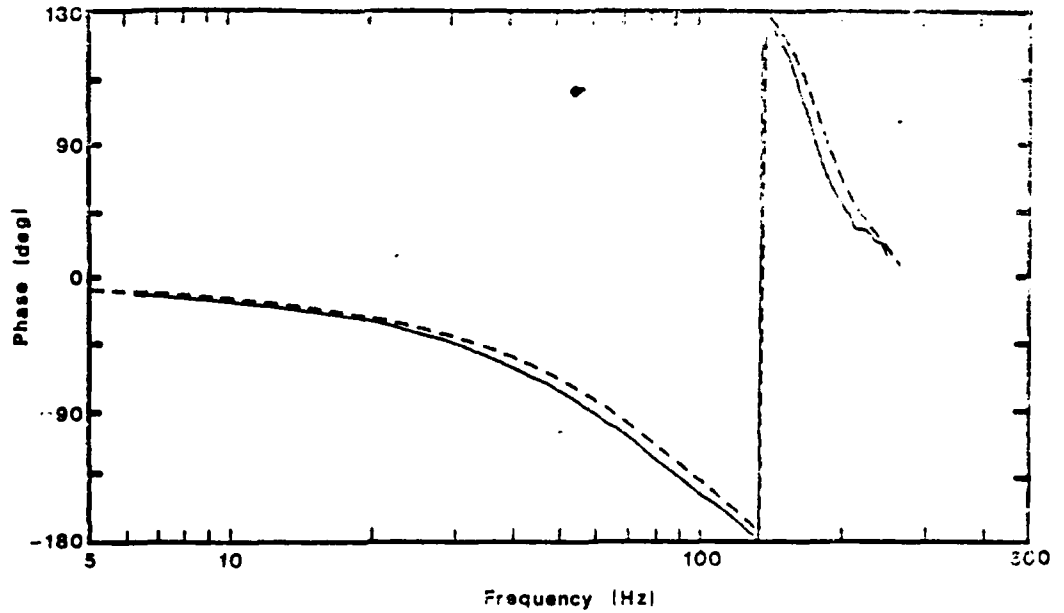
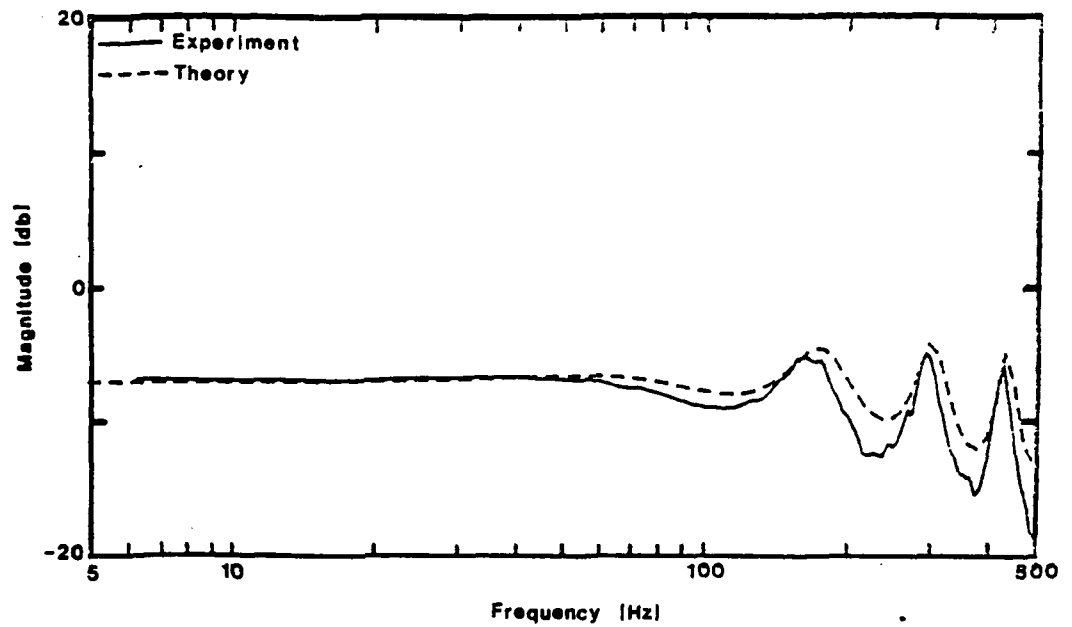
Data Set 100. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



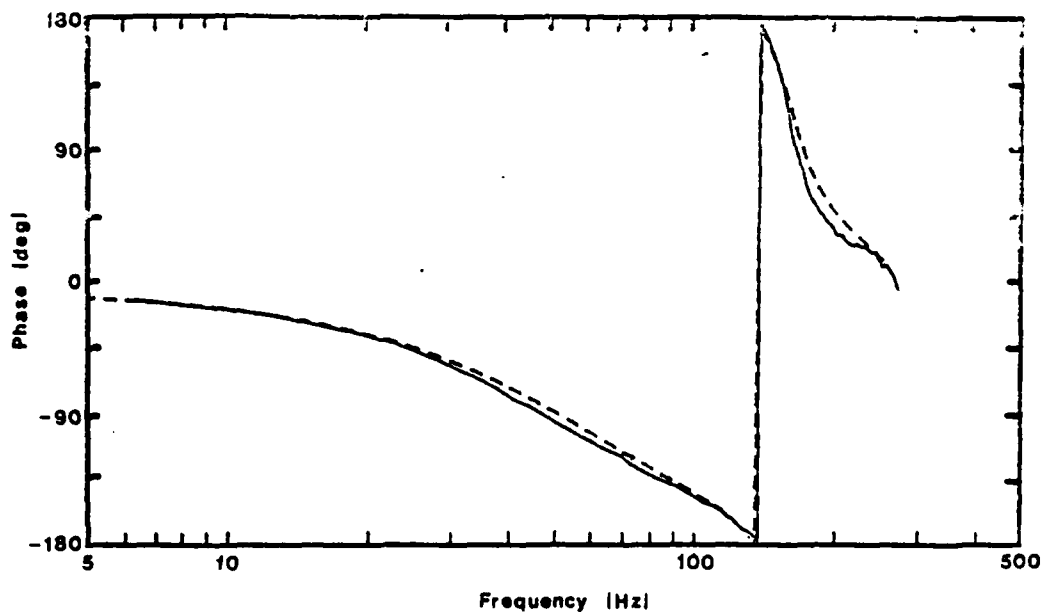
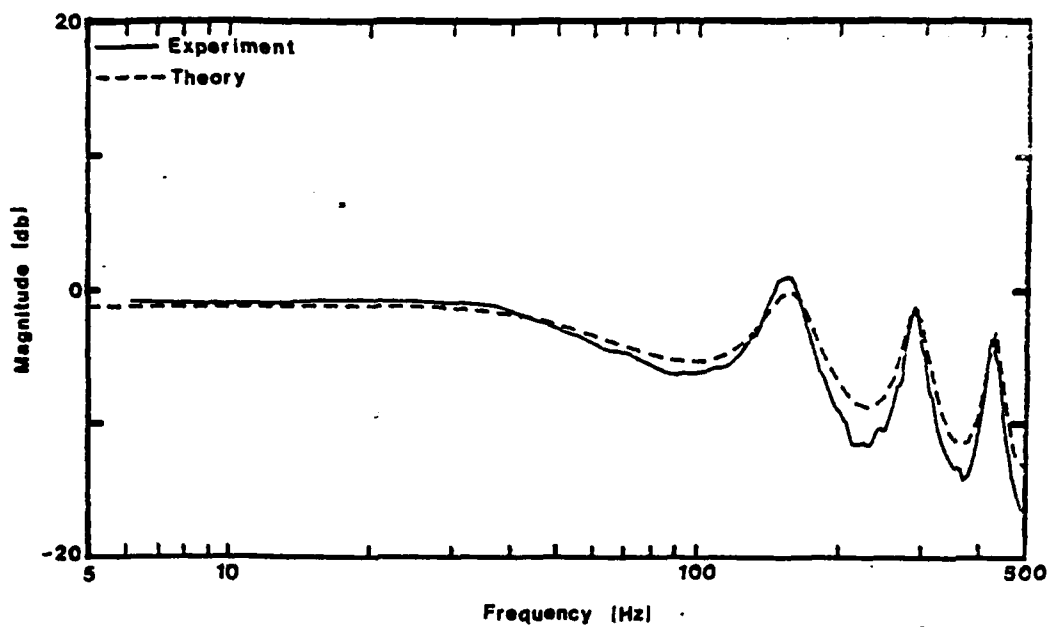
Data Set 101. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



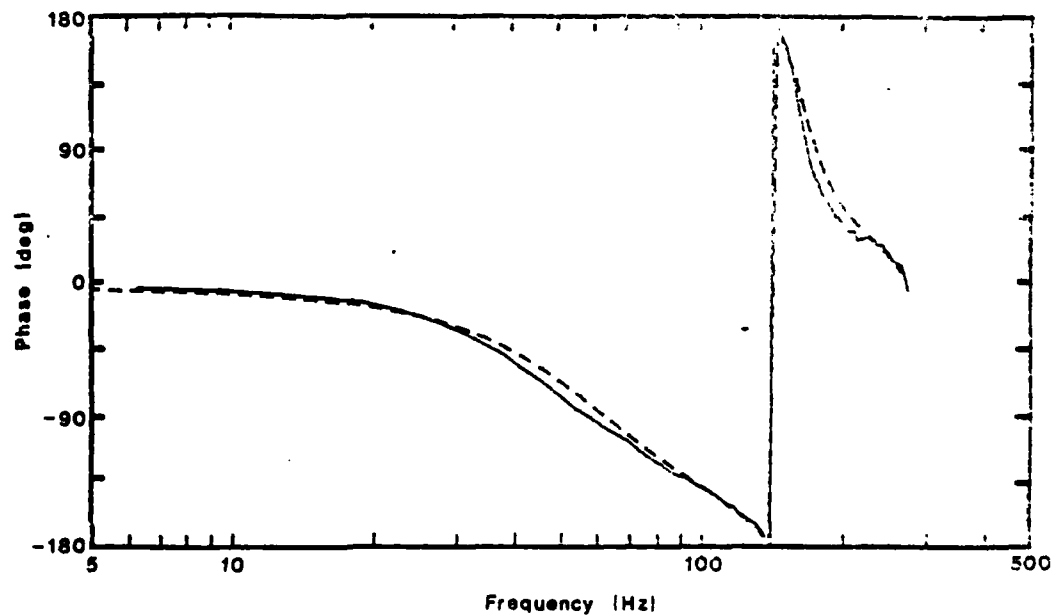
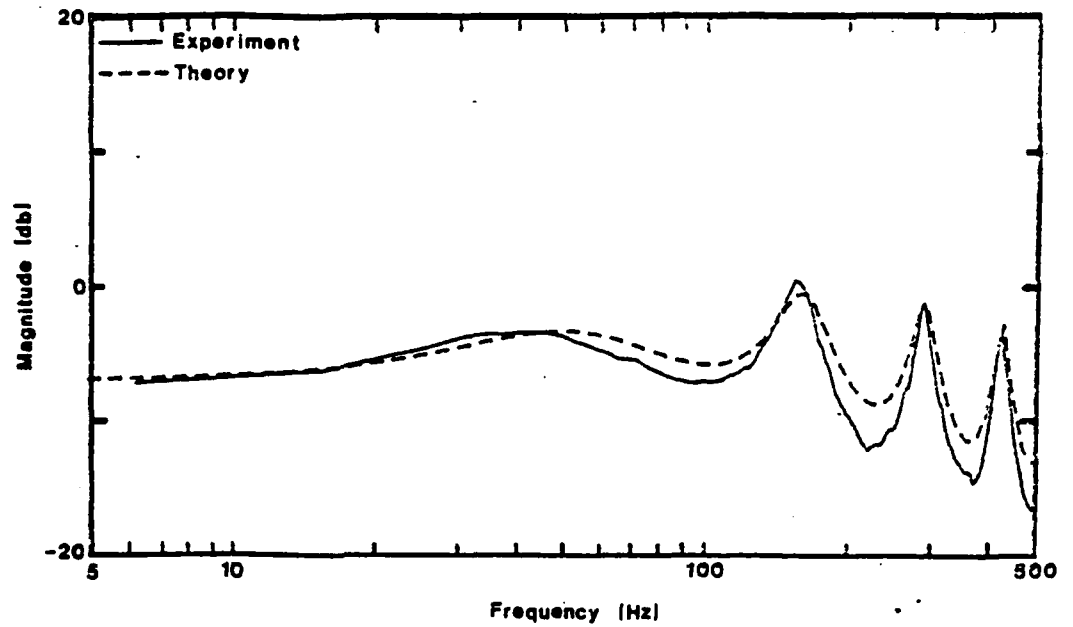
Data Set 102. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 716$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



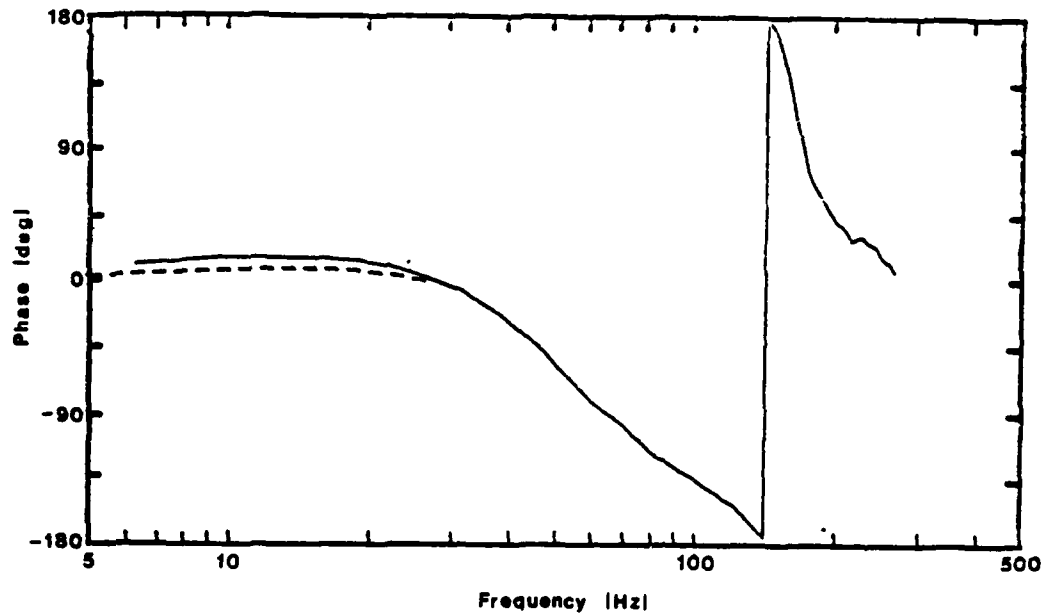
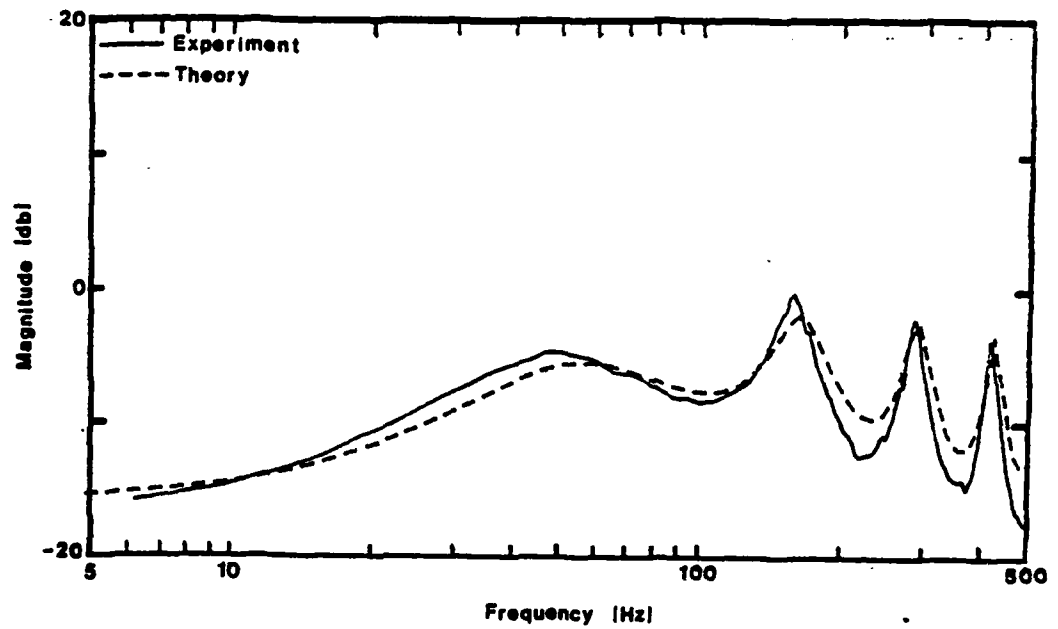
Data Set 103. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



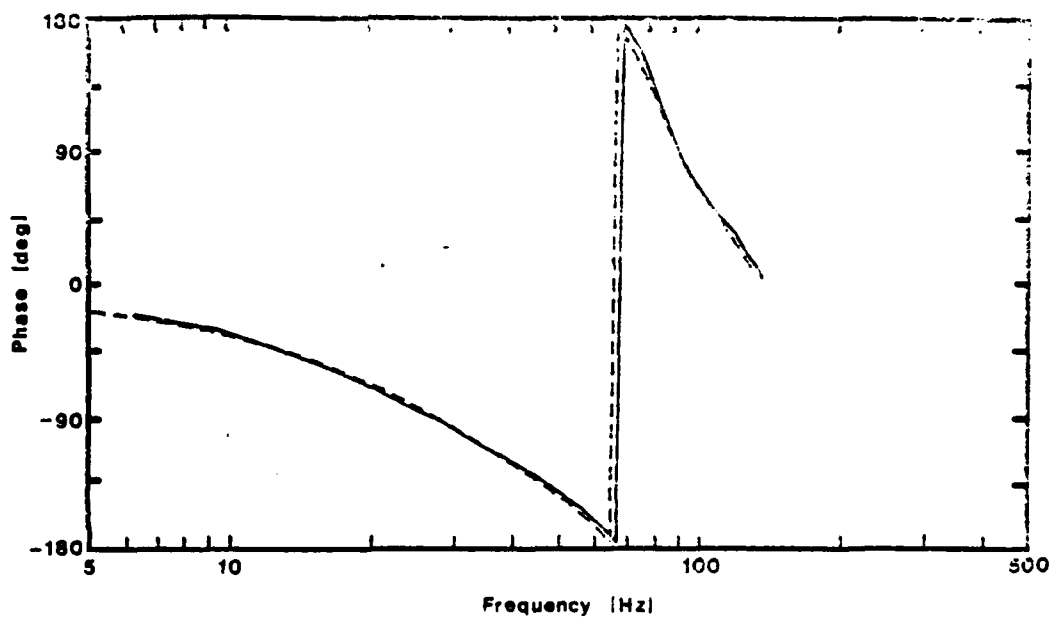
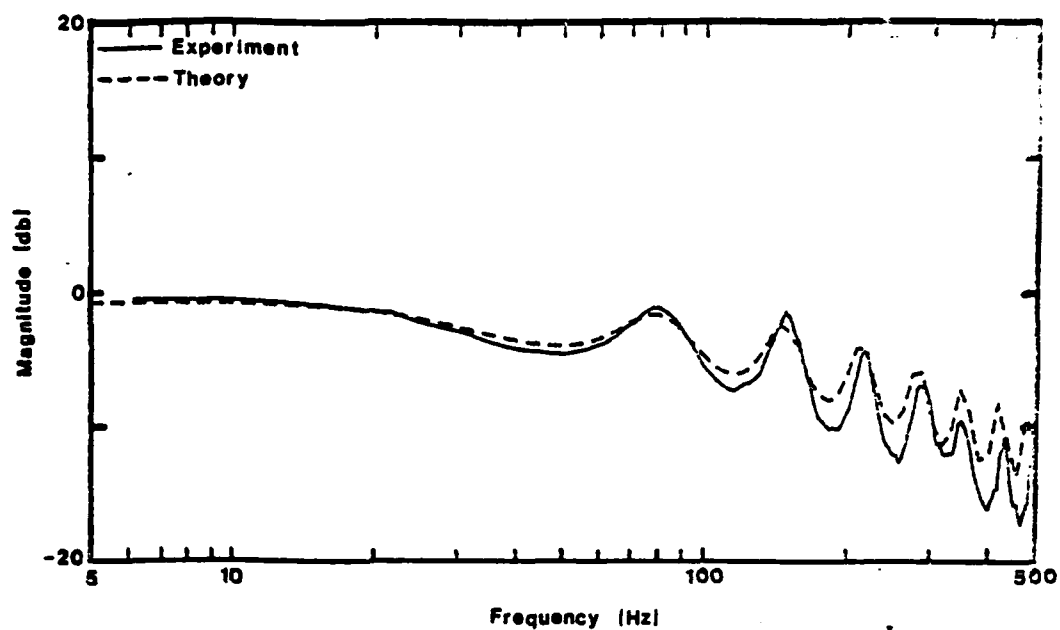
Data Set 104. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



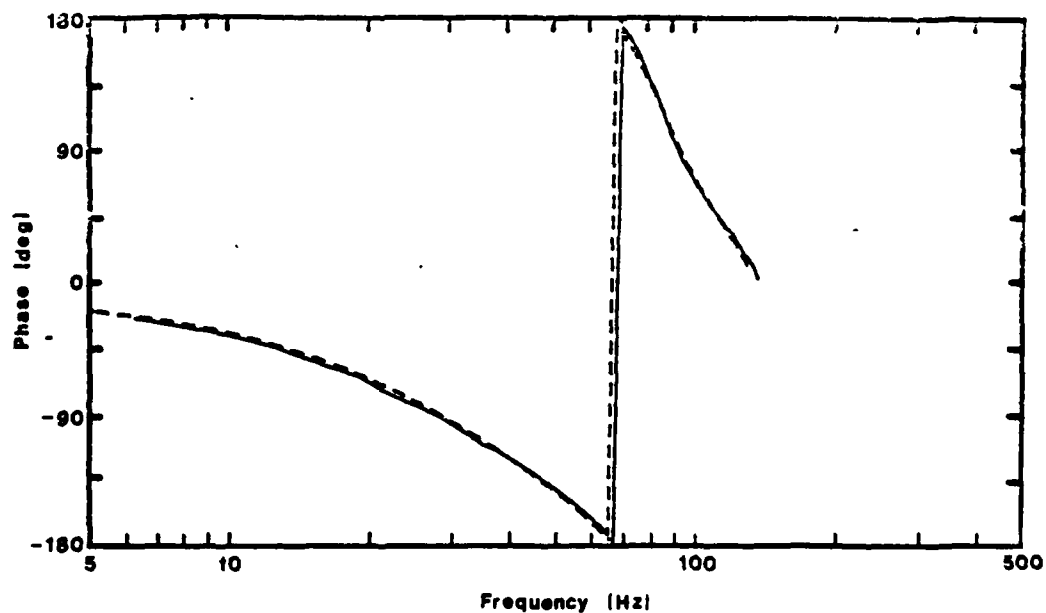
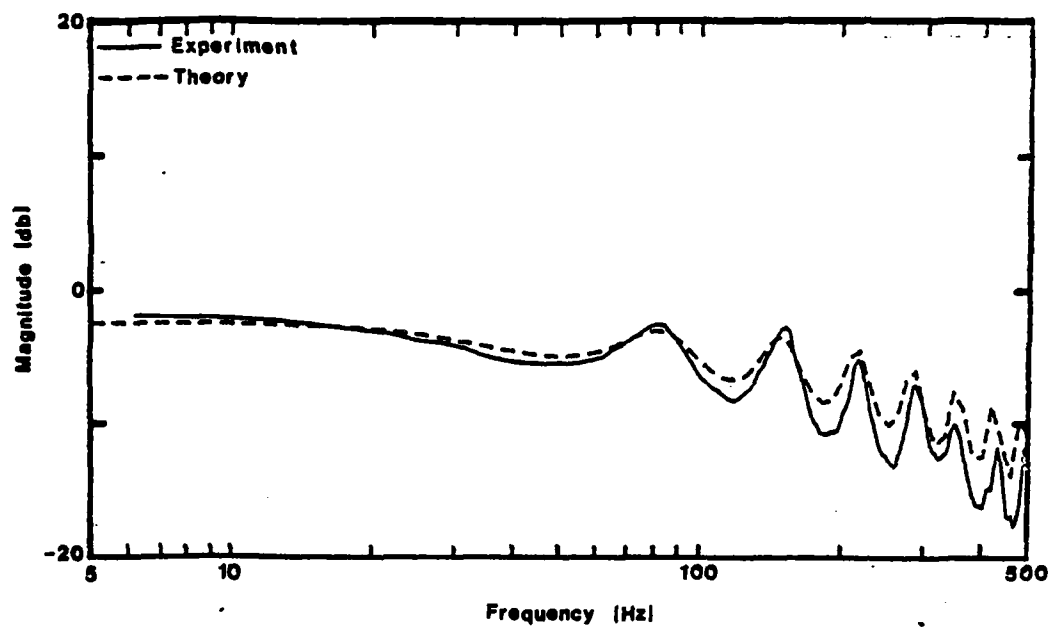
Data Set 105. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\lambda = 290$  mm,  $d = 1.63$  mm)



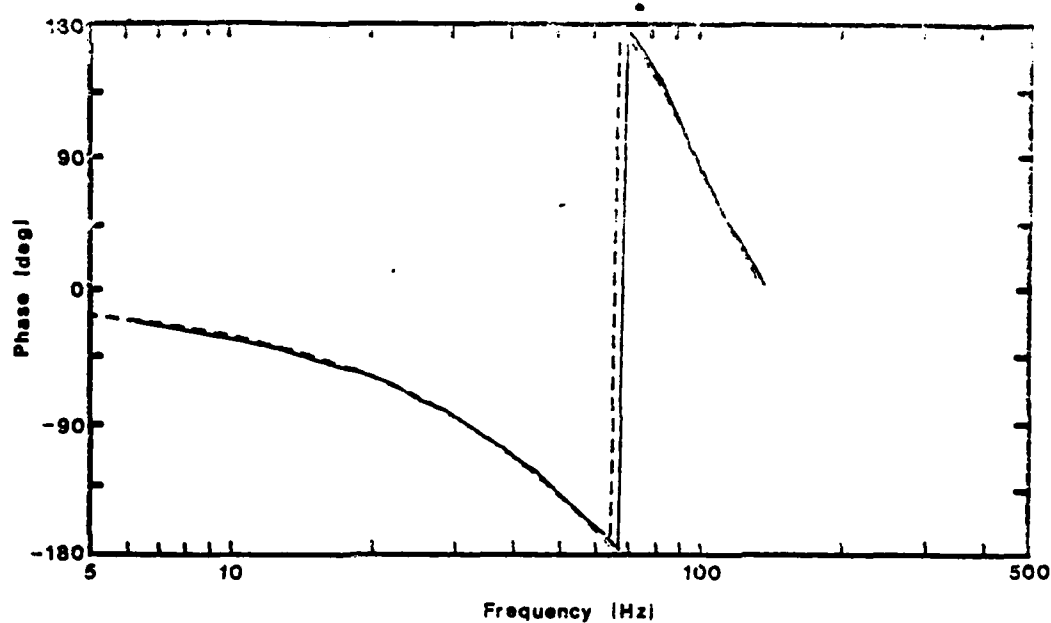
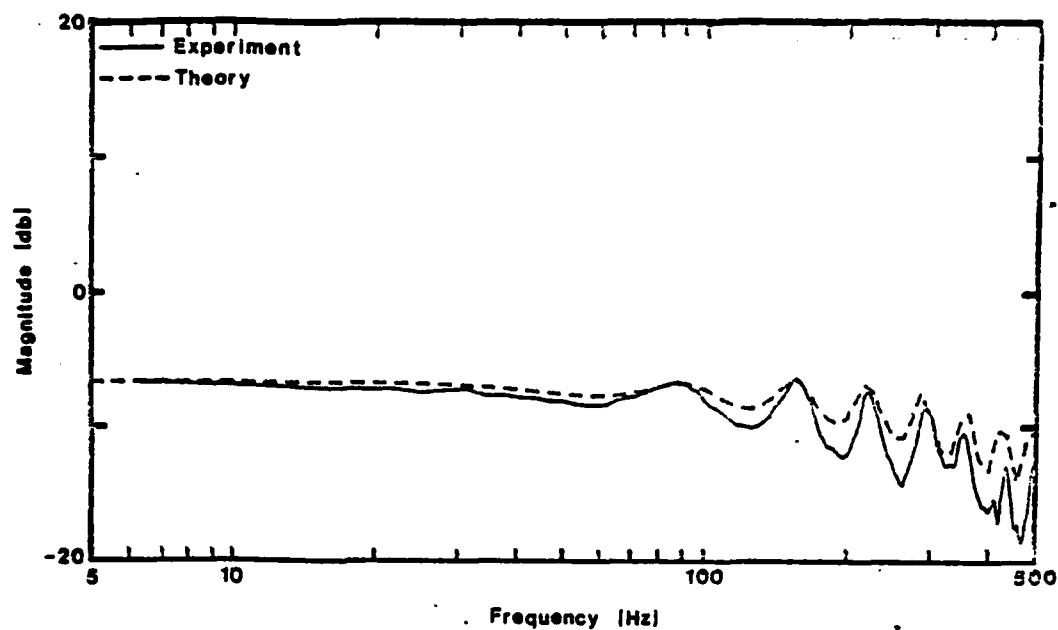
Data Set 106. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



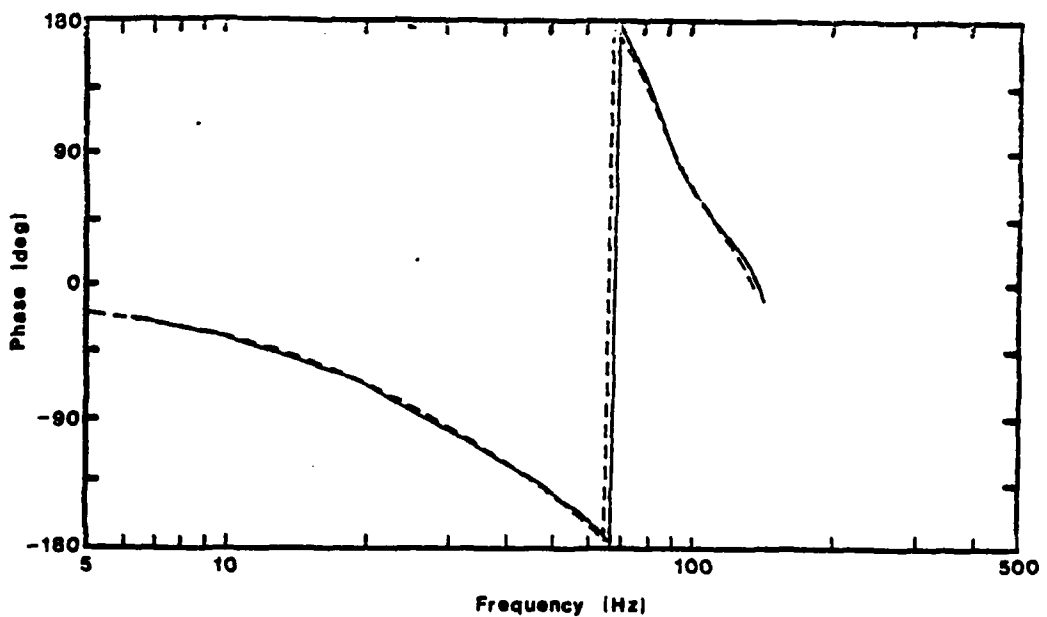
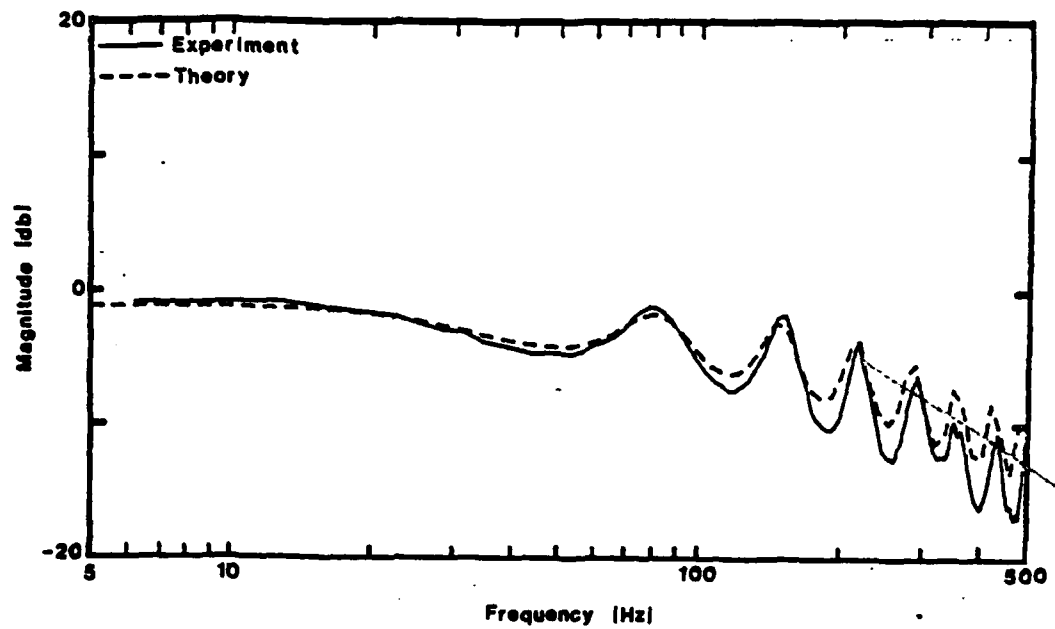
Data Set 107. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



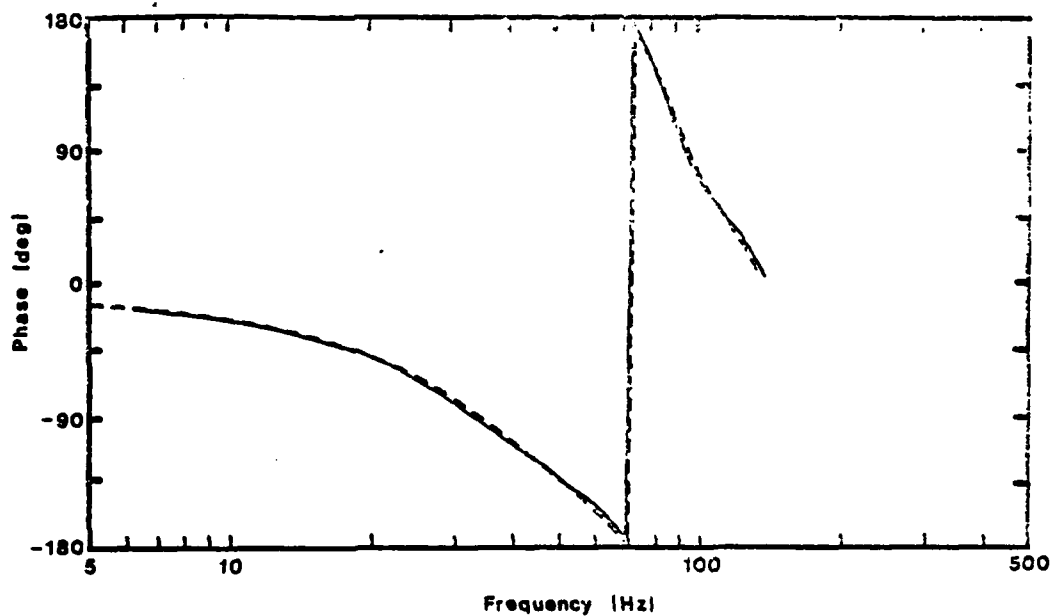
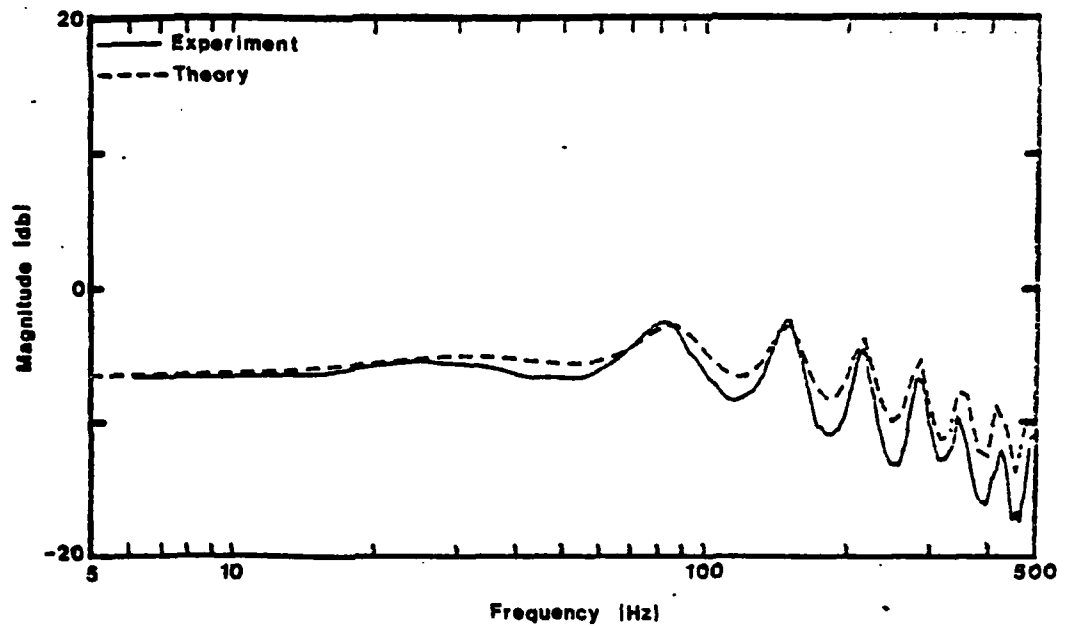
Data Set 108. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



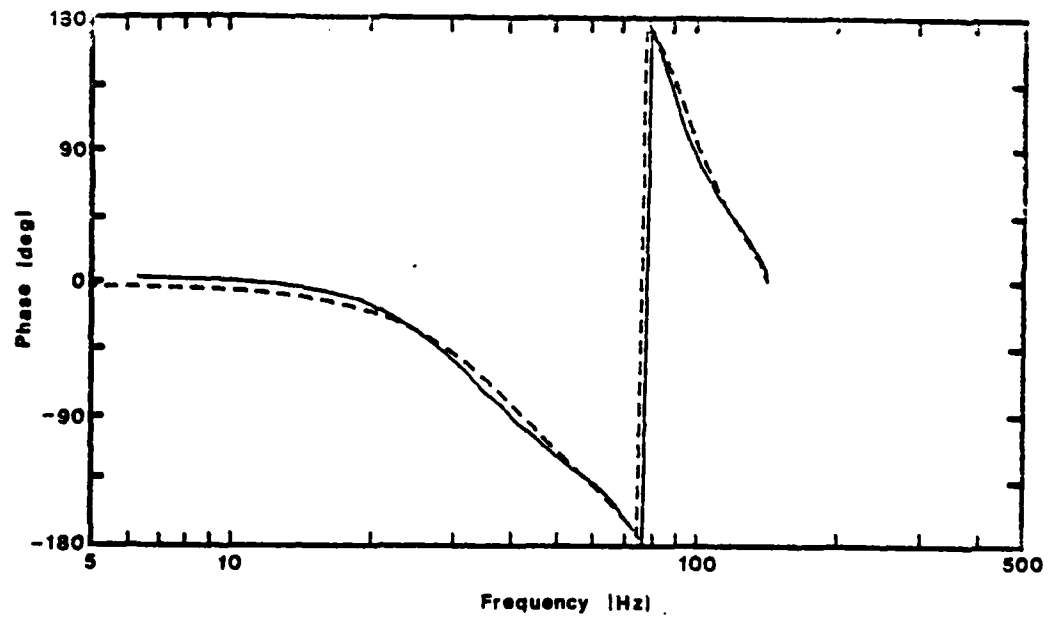
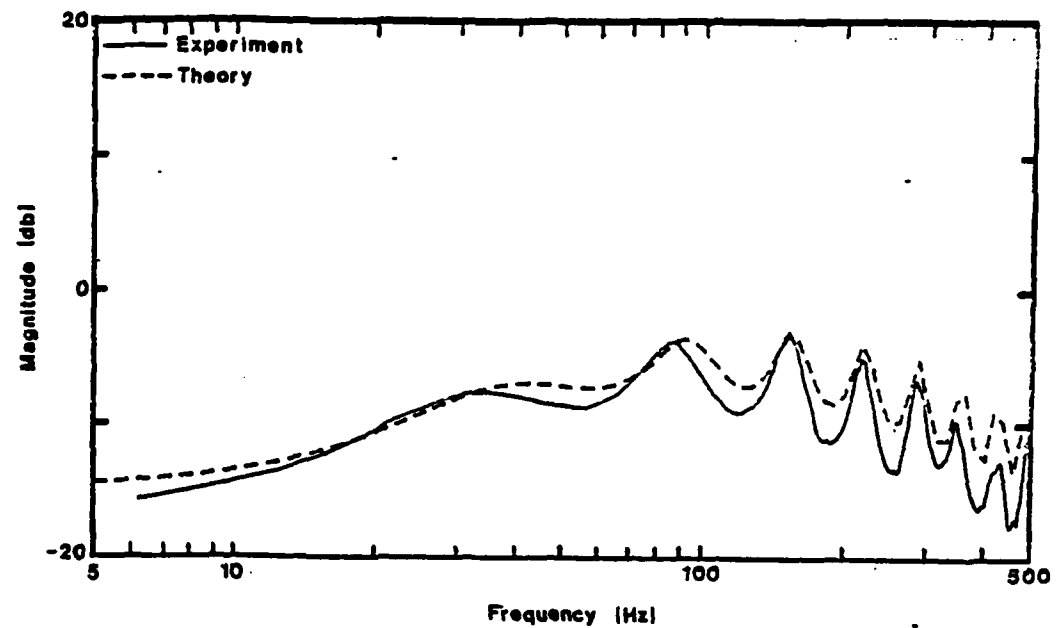
Data Set 109. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



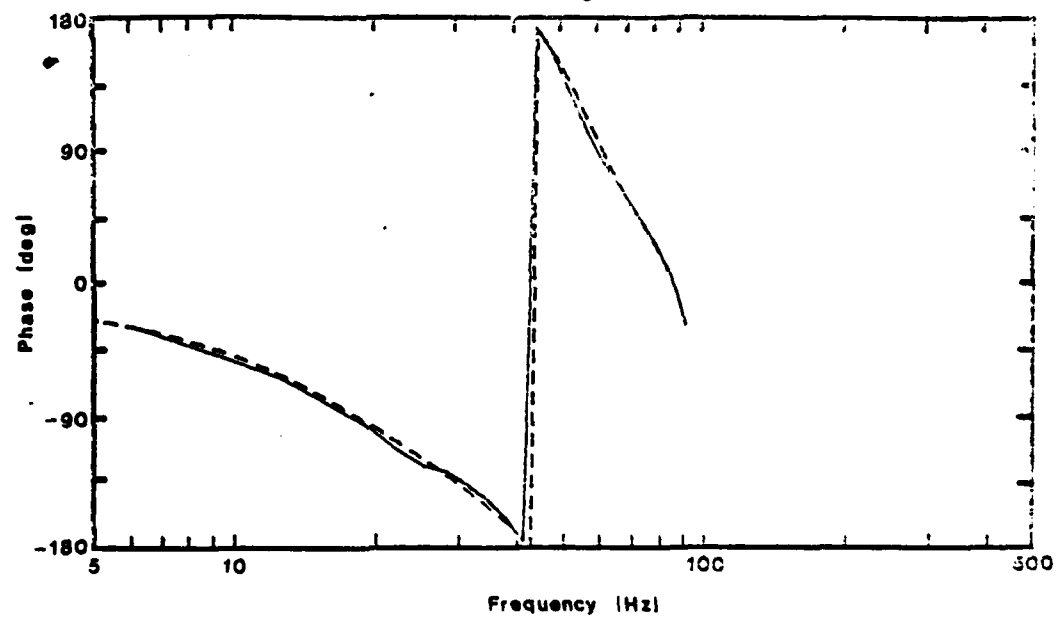
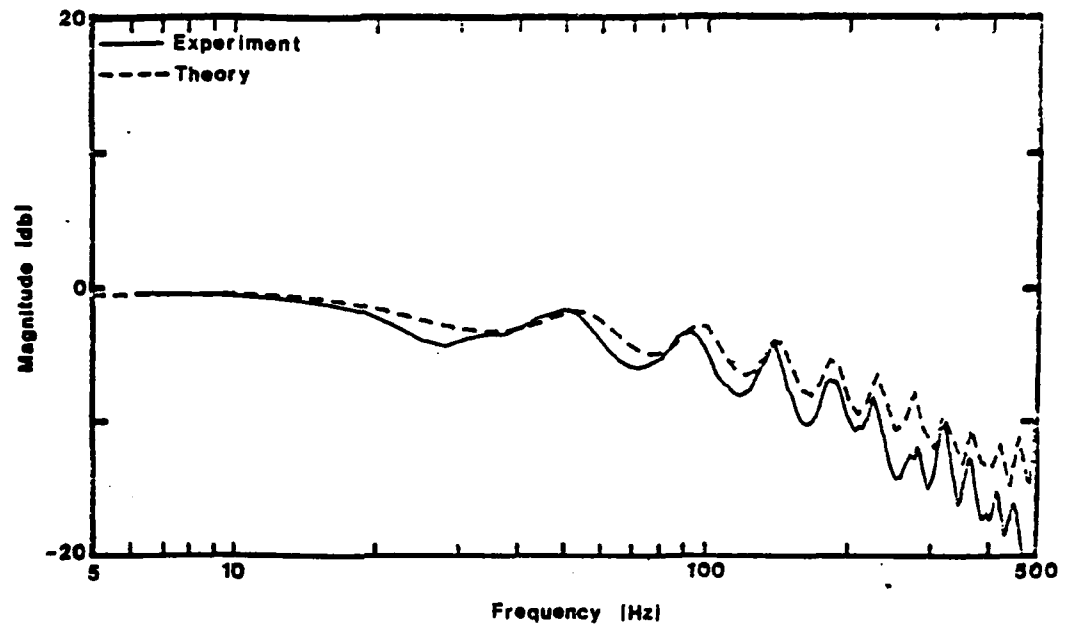
Data Set 110. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



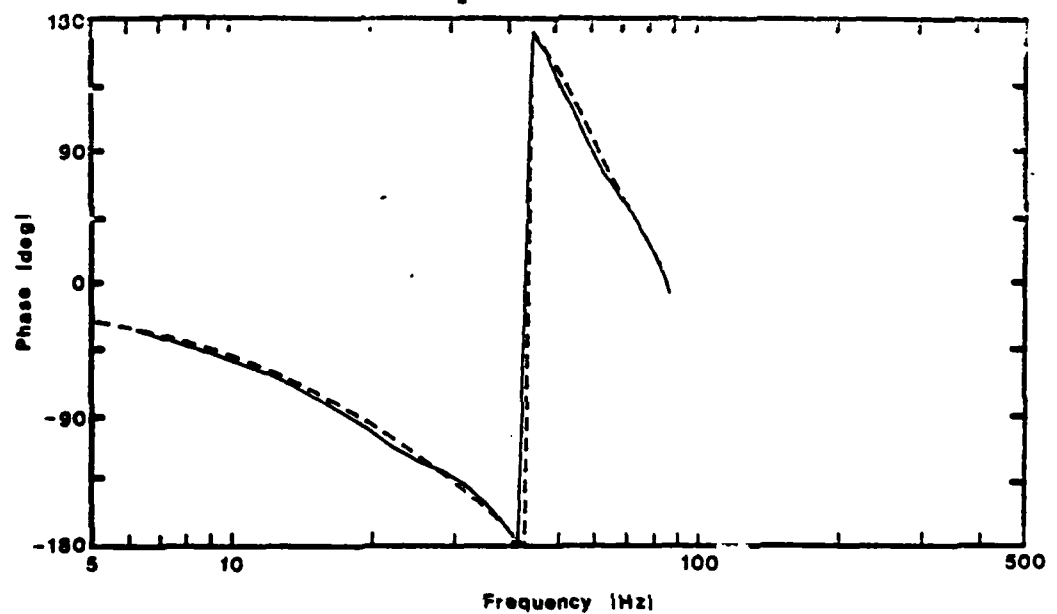
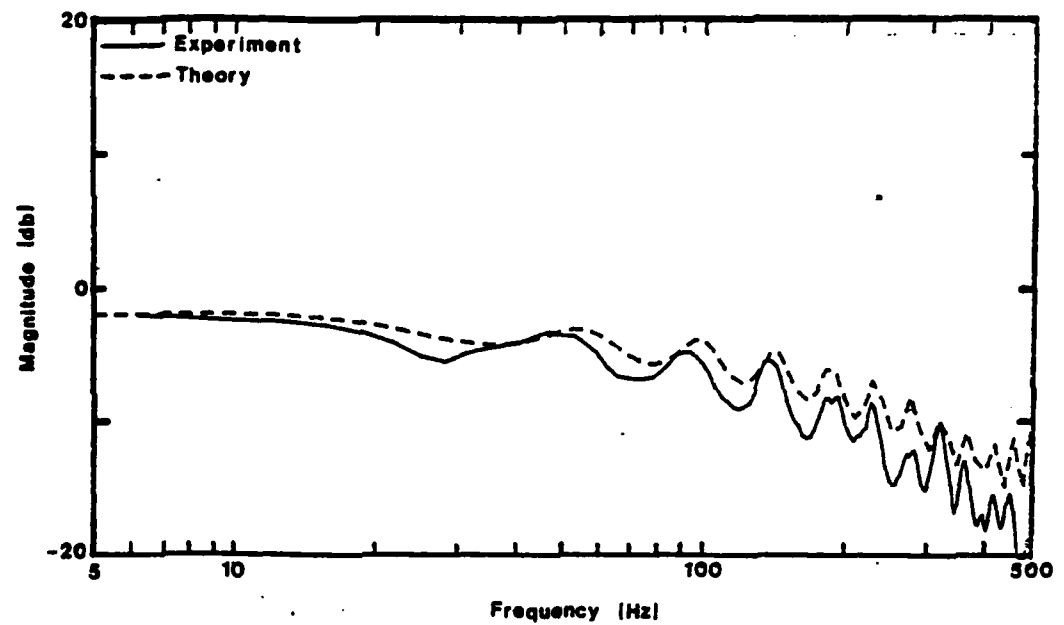
Data Set 111. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\lambda = 290$  mm,  $d = 1.63$  mm)



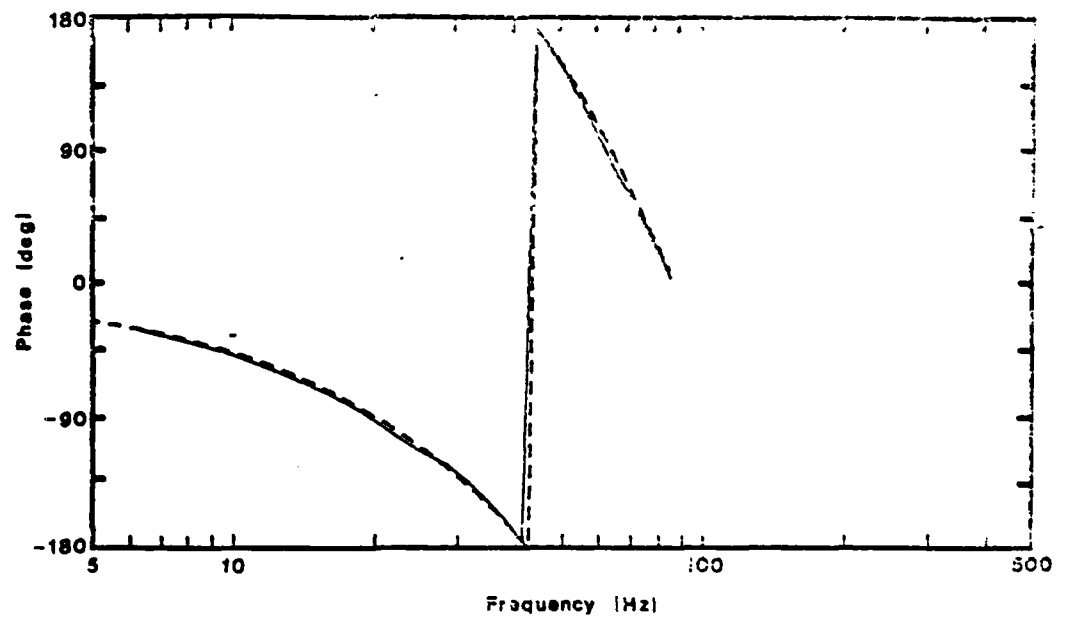
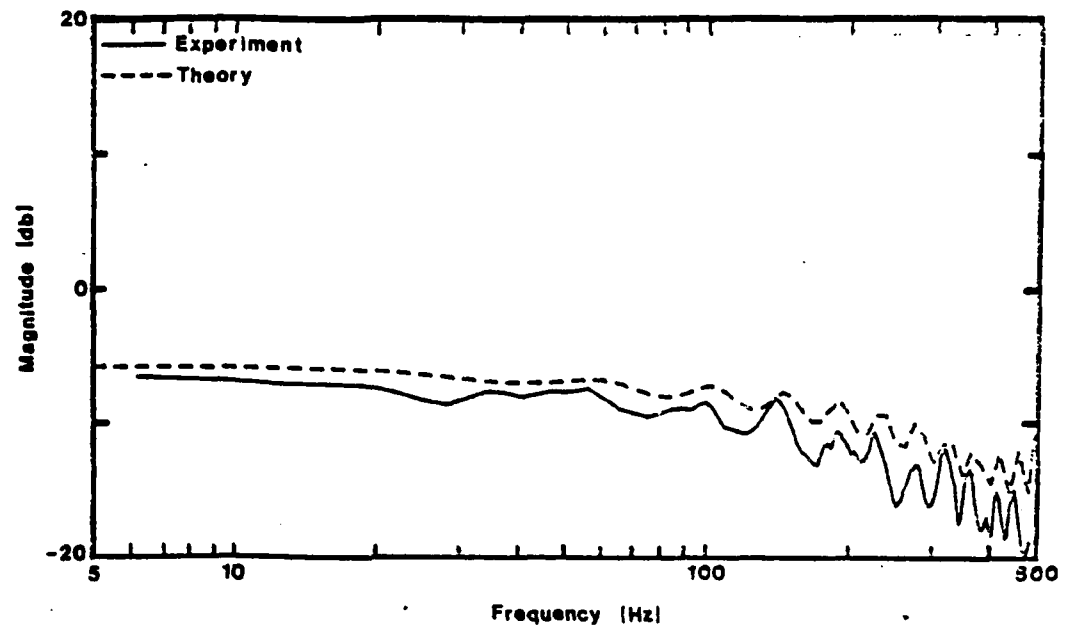
Data Set 112. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



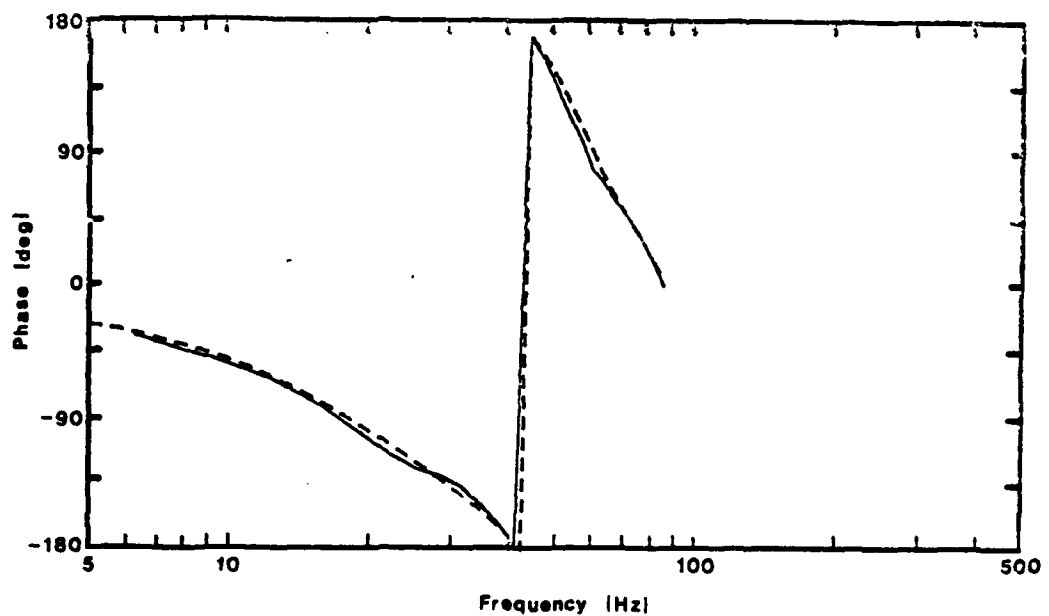
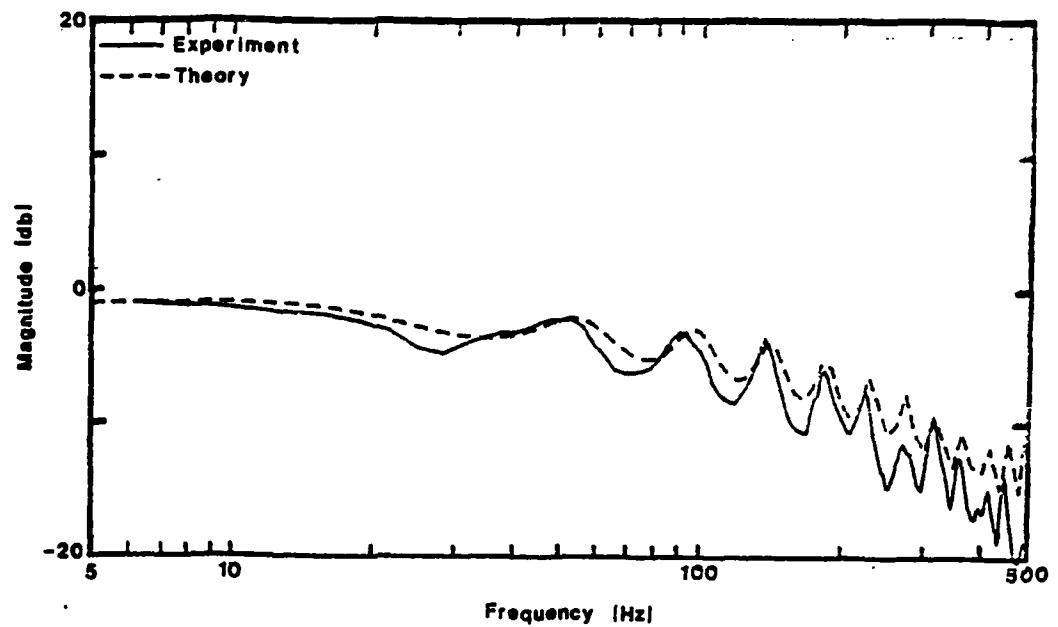
Data Set 113. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



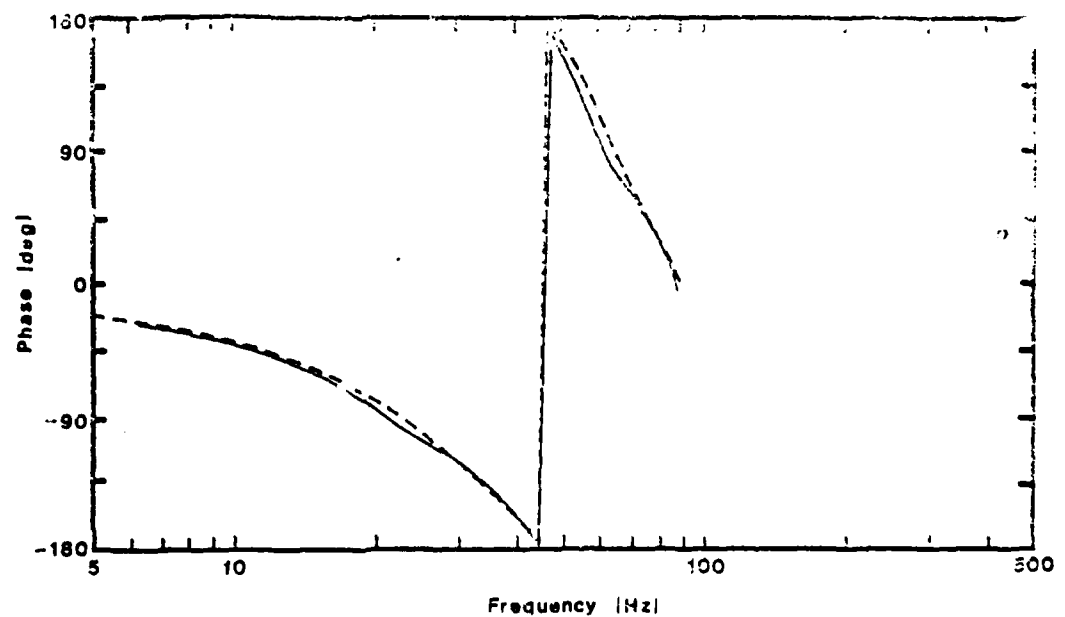
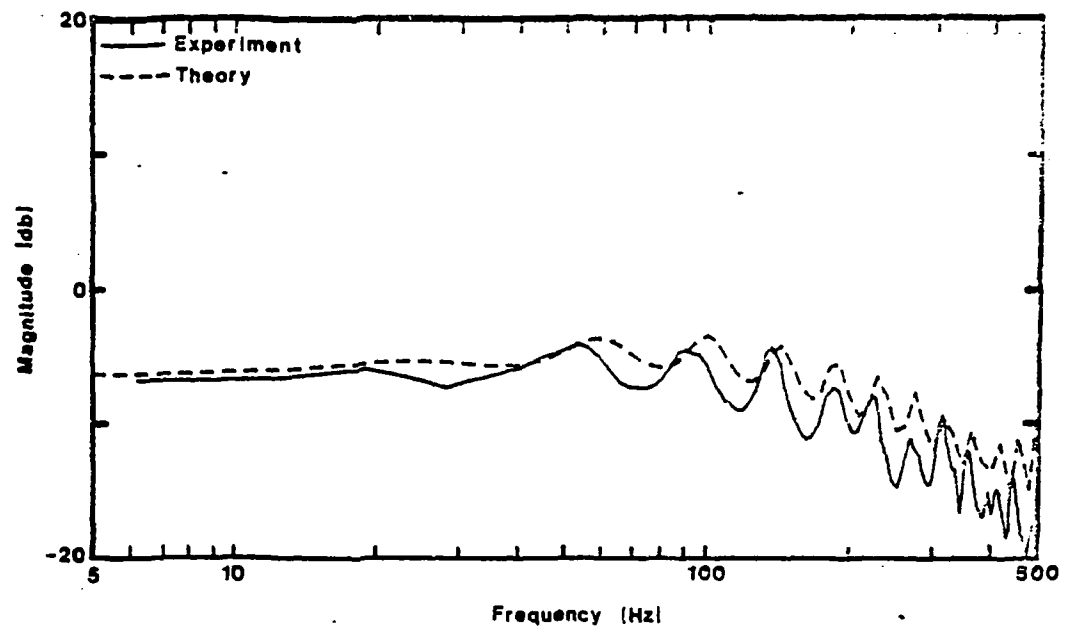
Data Set 114. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



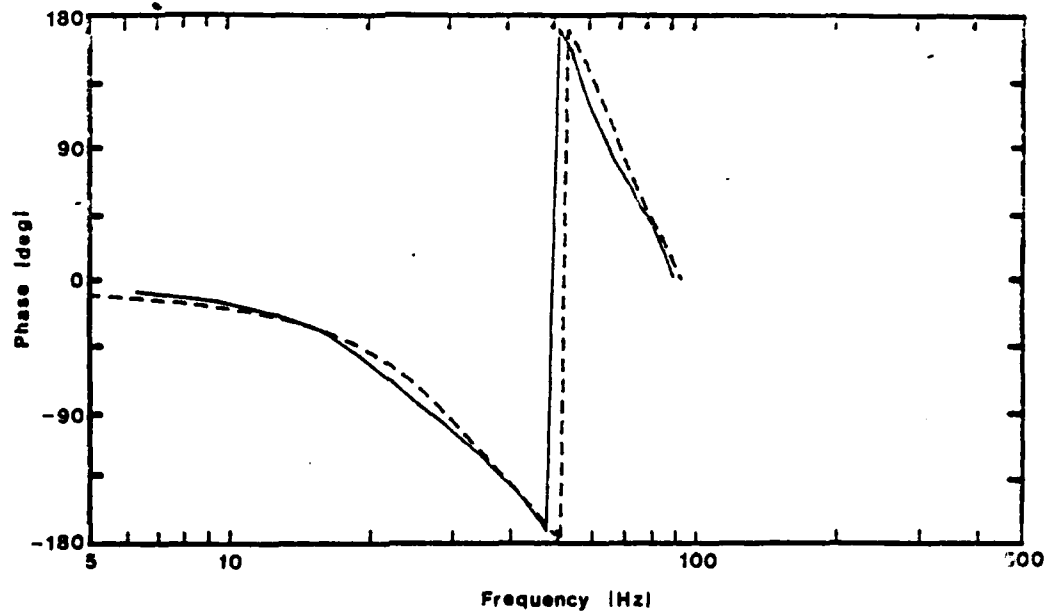
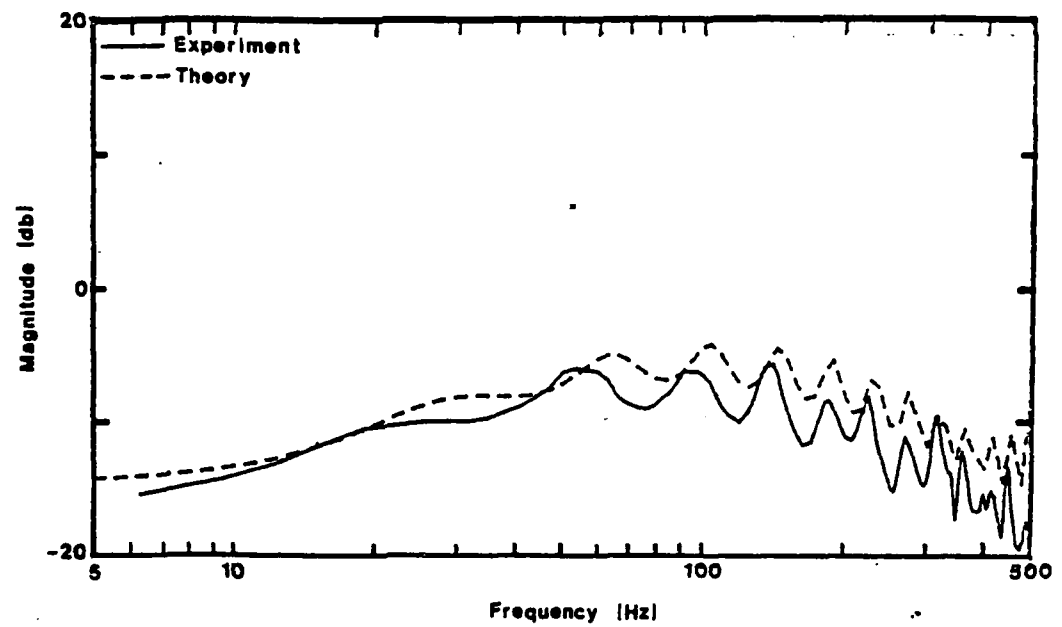
Data Set 115. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



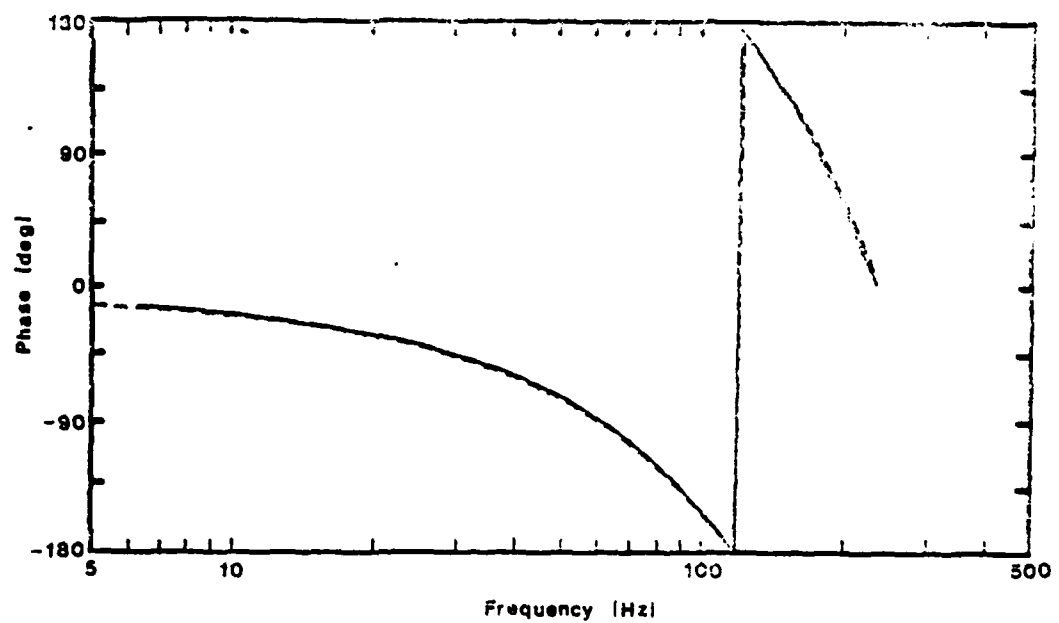
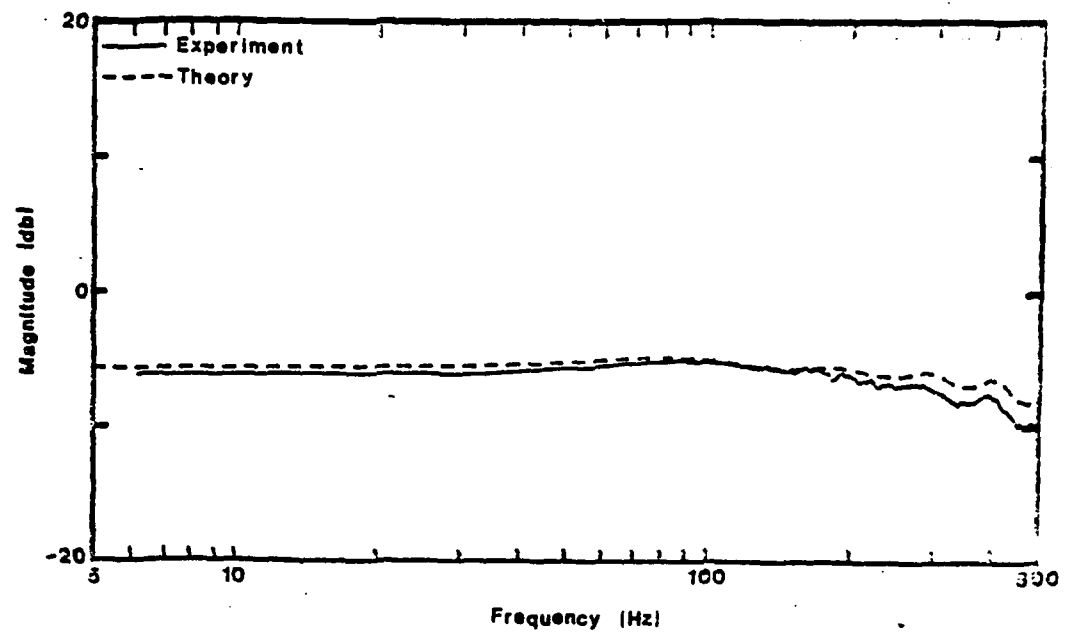
Data Set 116. Line with Source Impedance and Load Impedance  
 ( $l = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $l = 297$  mm,  $d = .88$  mm)



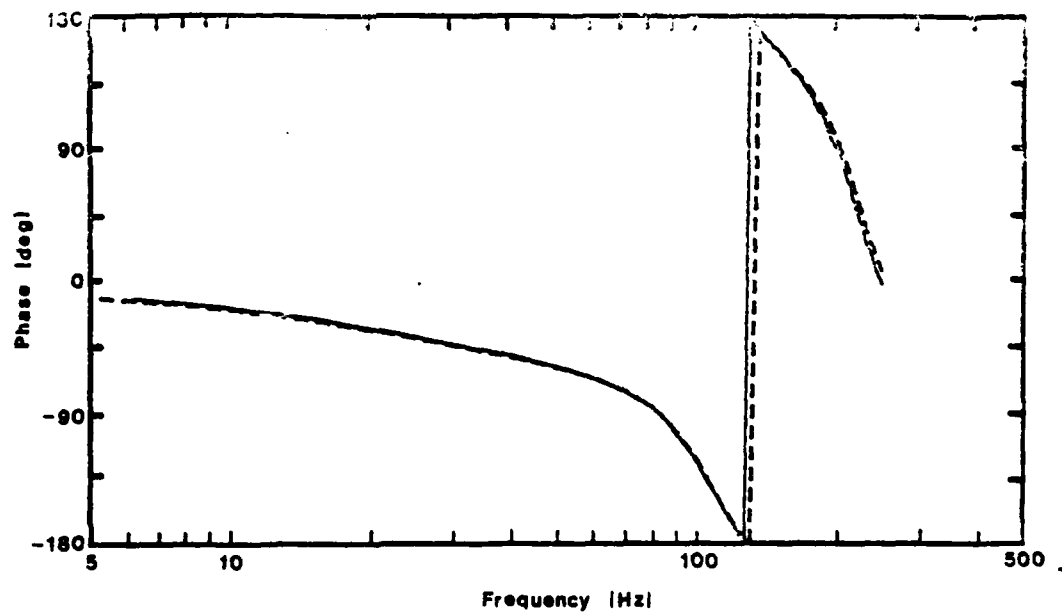
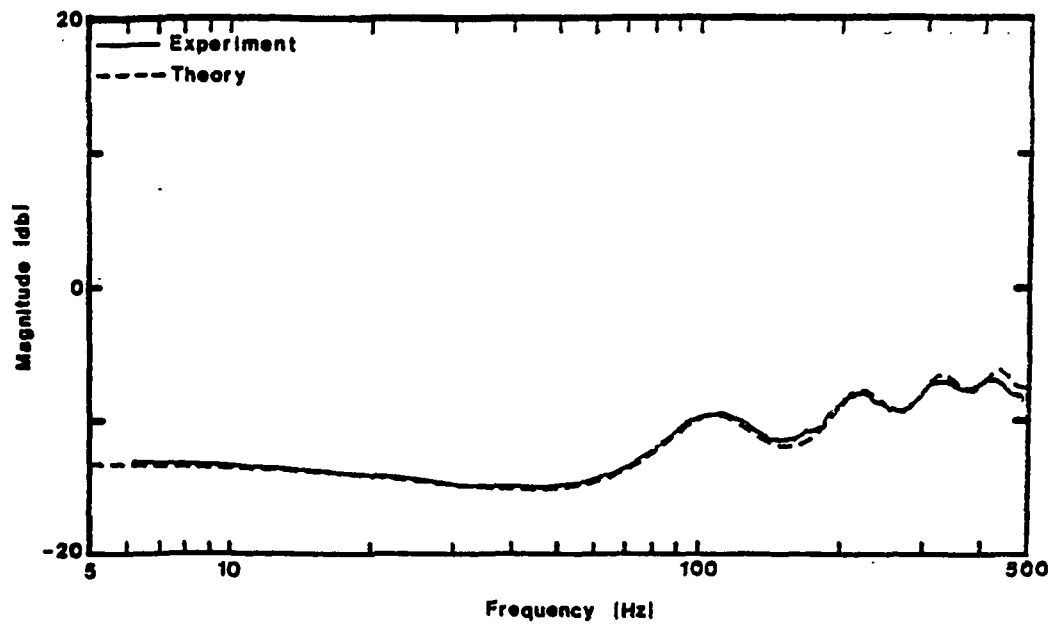
Data Set 117. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



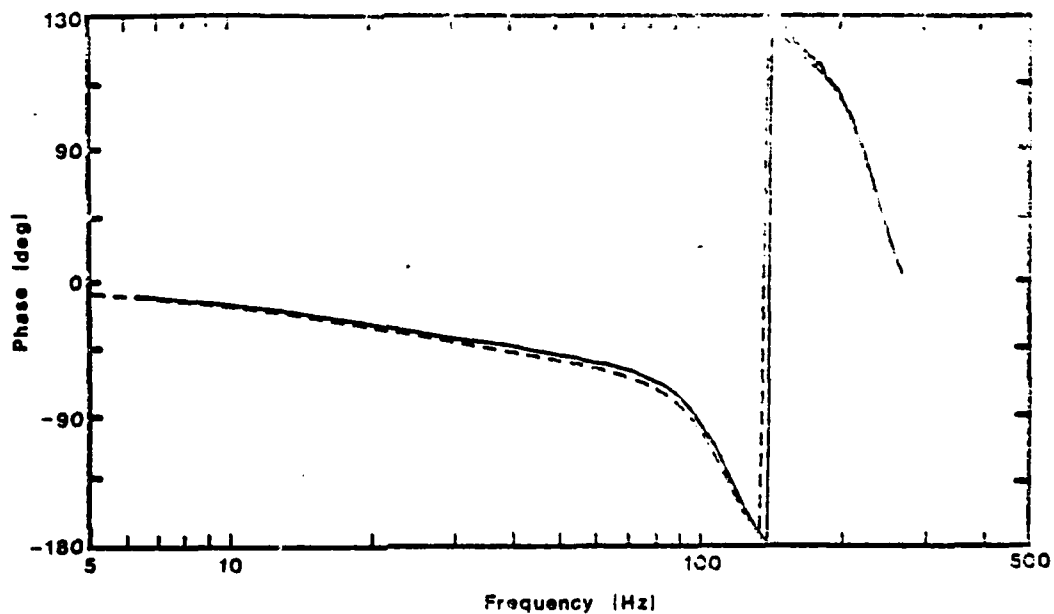
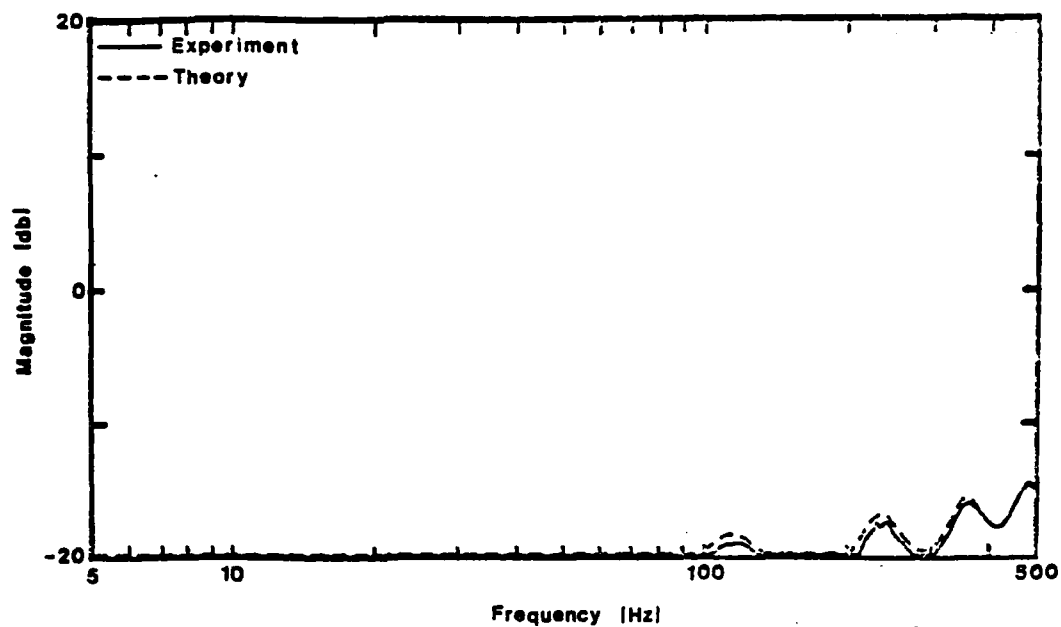
Data Set 118. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #2, 4 tubes,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



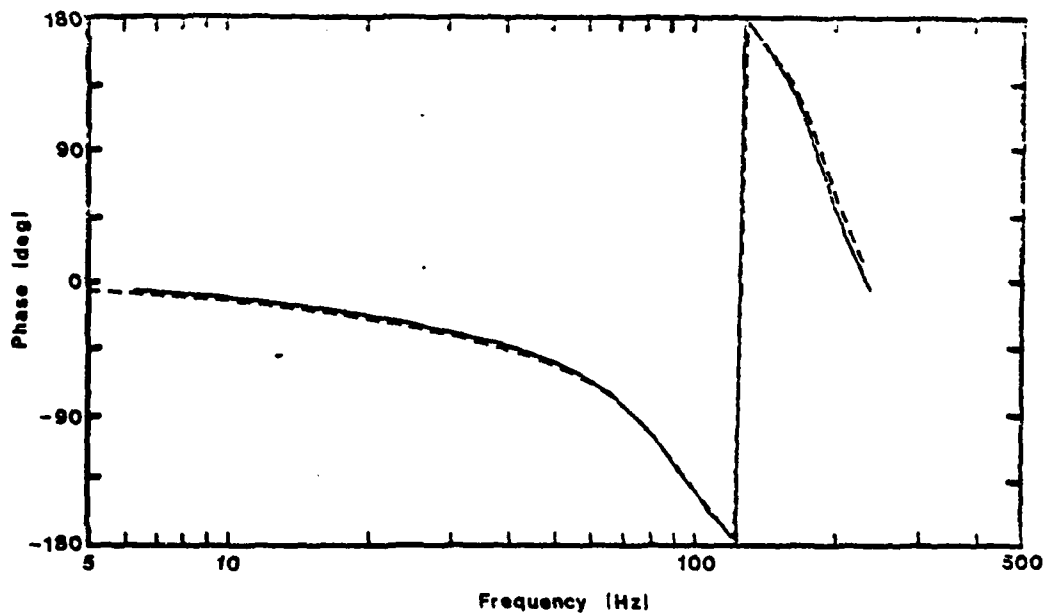
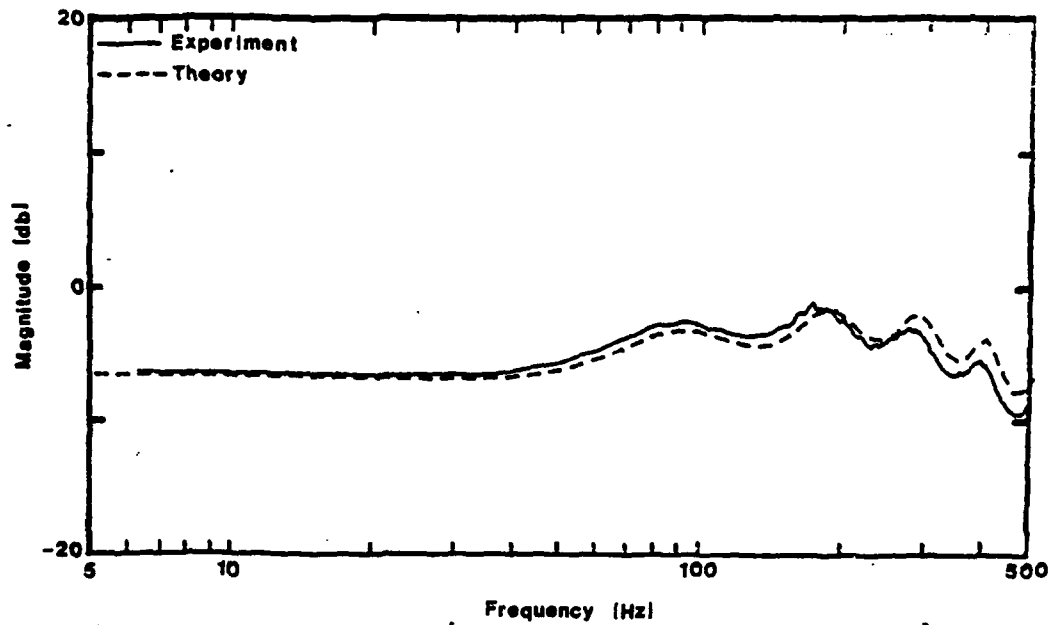
Data Set 119. Line with Source Impedance and Load Impedance  
( $\lambda = 4.8$  m,  $d = 1.7$  mm, Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\lambda = 24.2$  mm,  $d = .427$  mm)



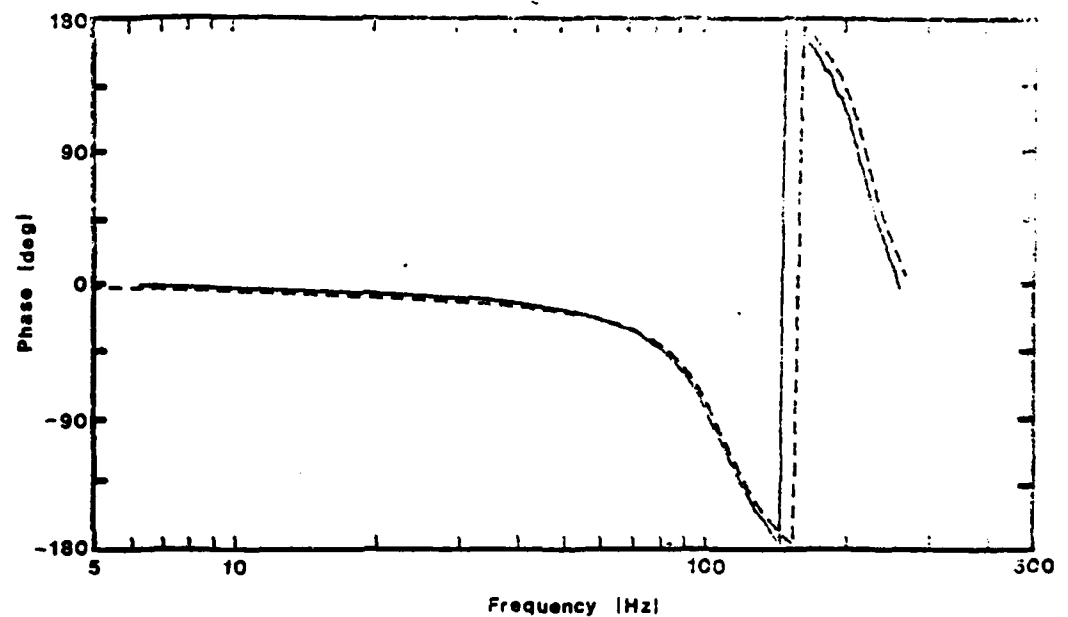
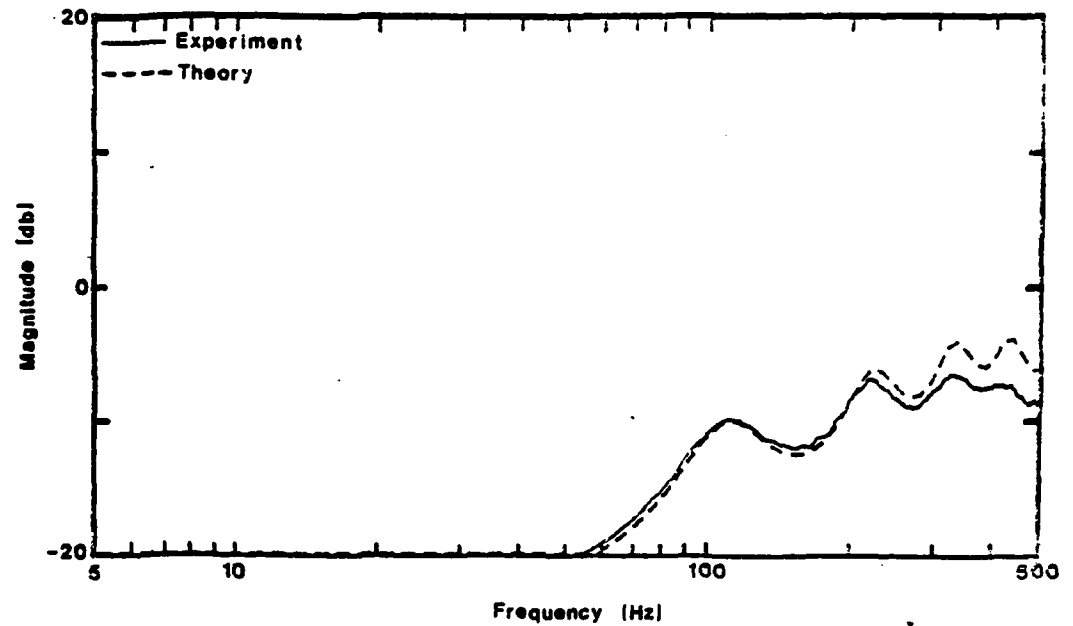
Data Set 120. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



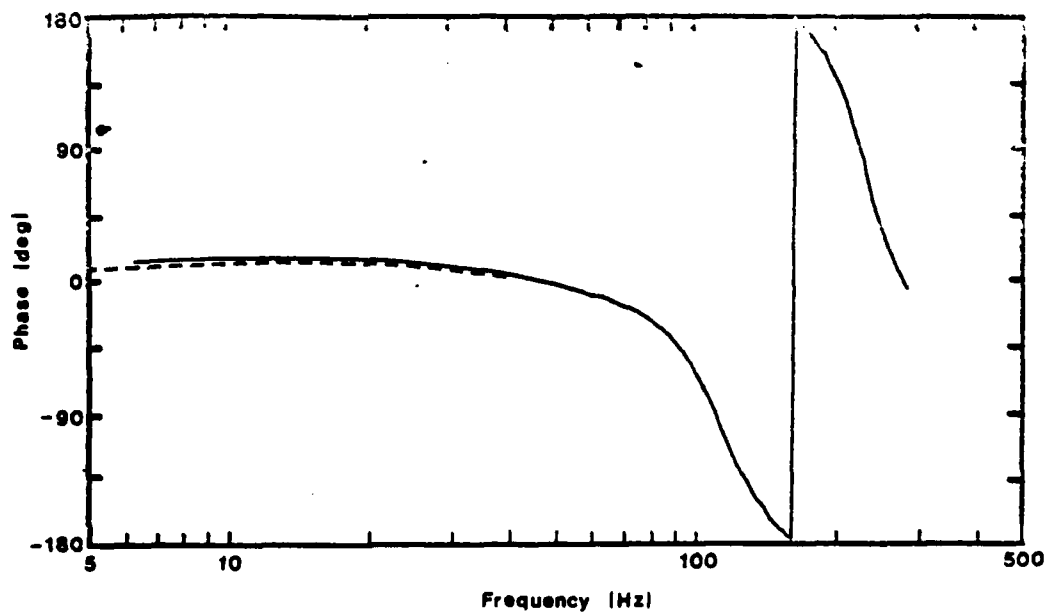
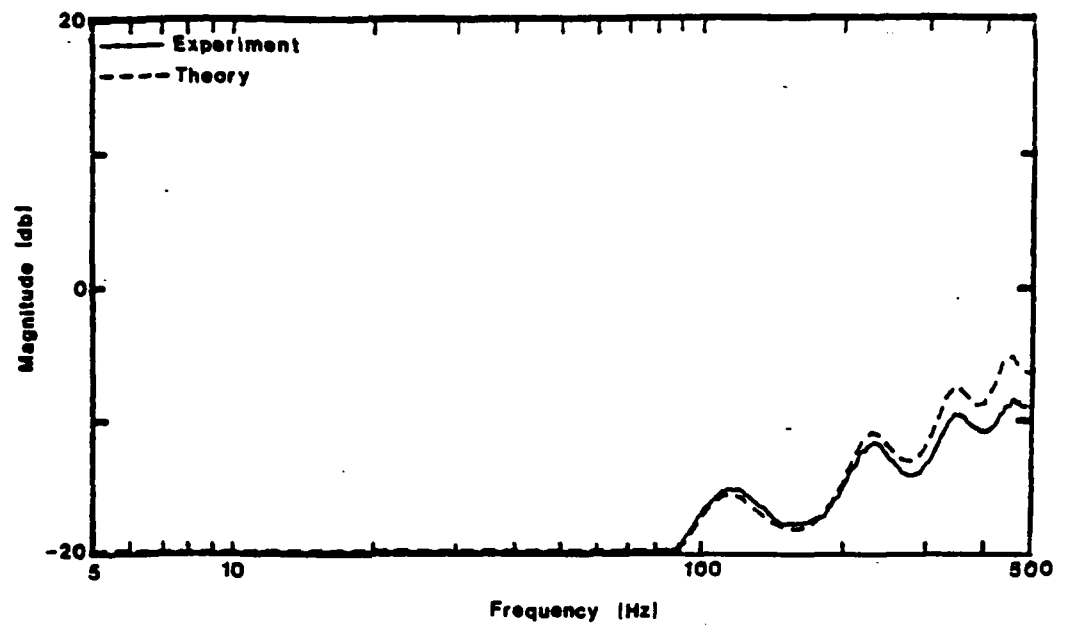
Data Set 121. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\lambda = 52$  mm,  $d = .716$  mm)



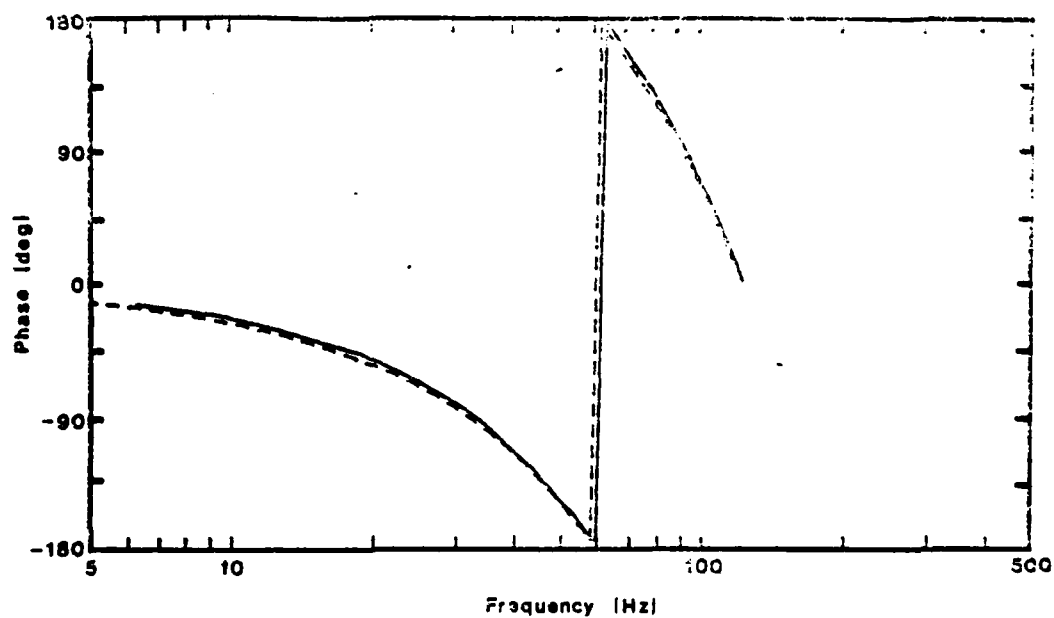
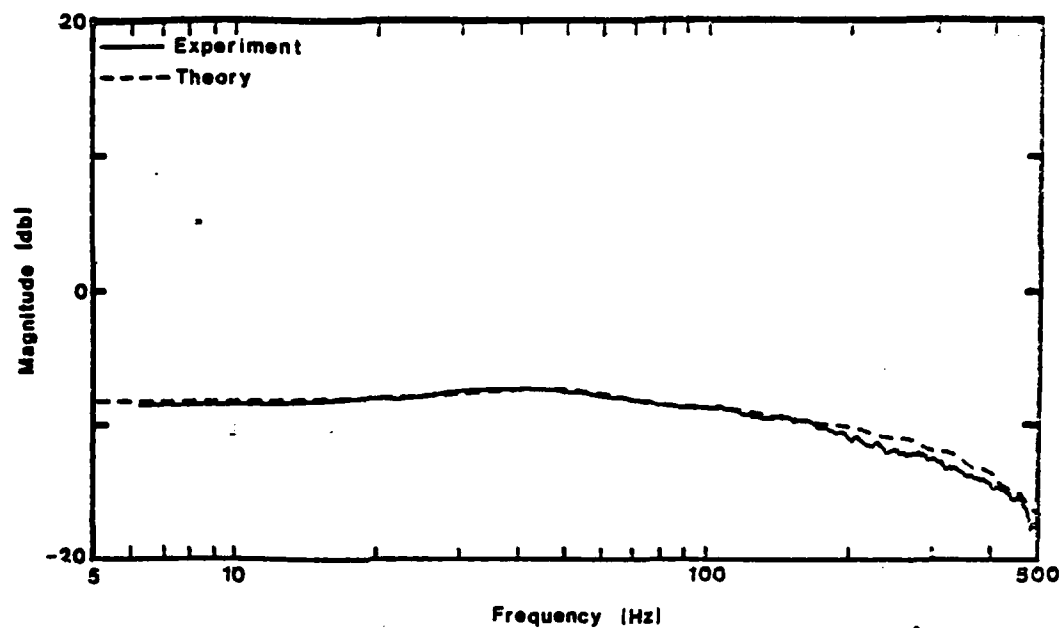
Data Set 122. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



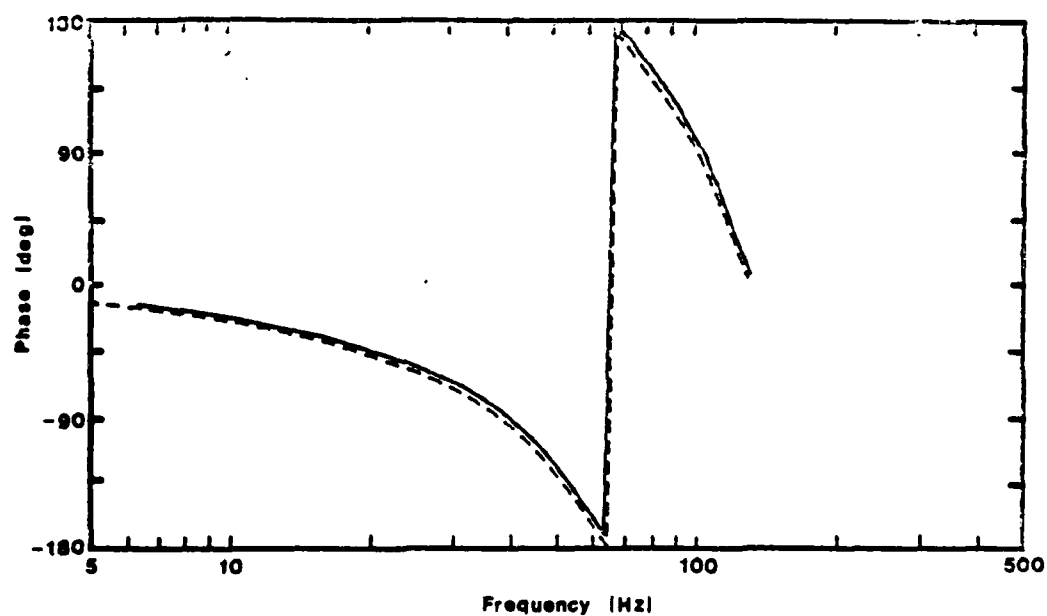
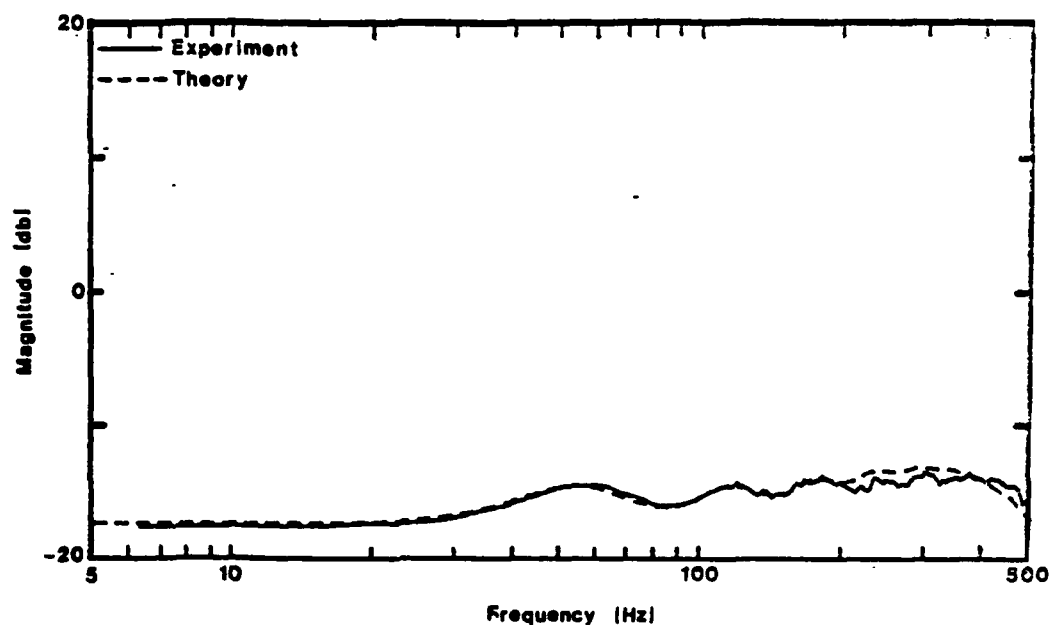
Data Set 123. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



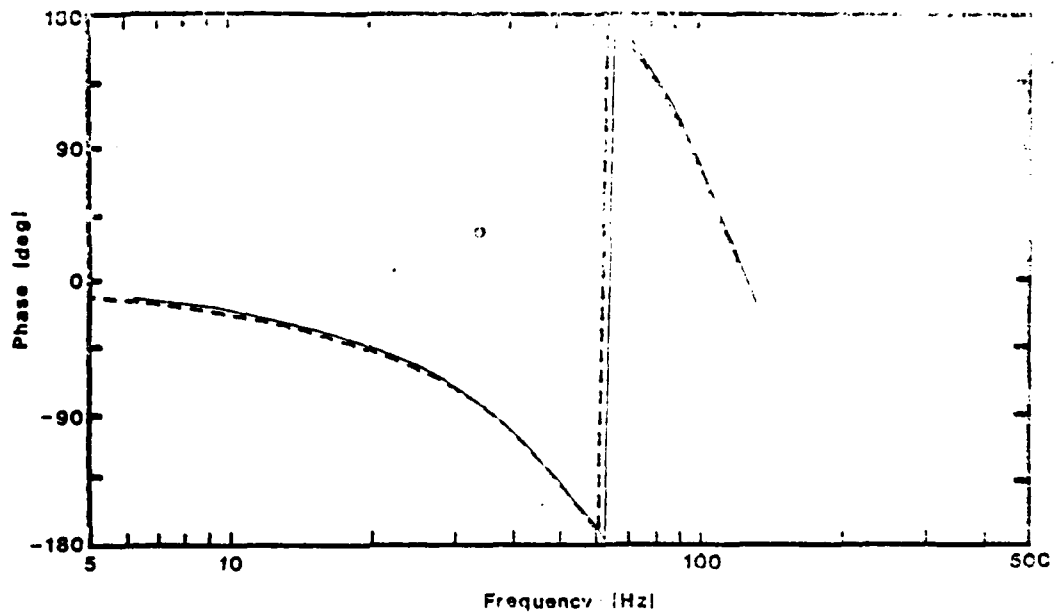
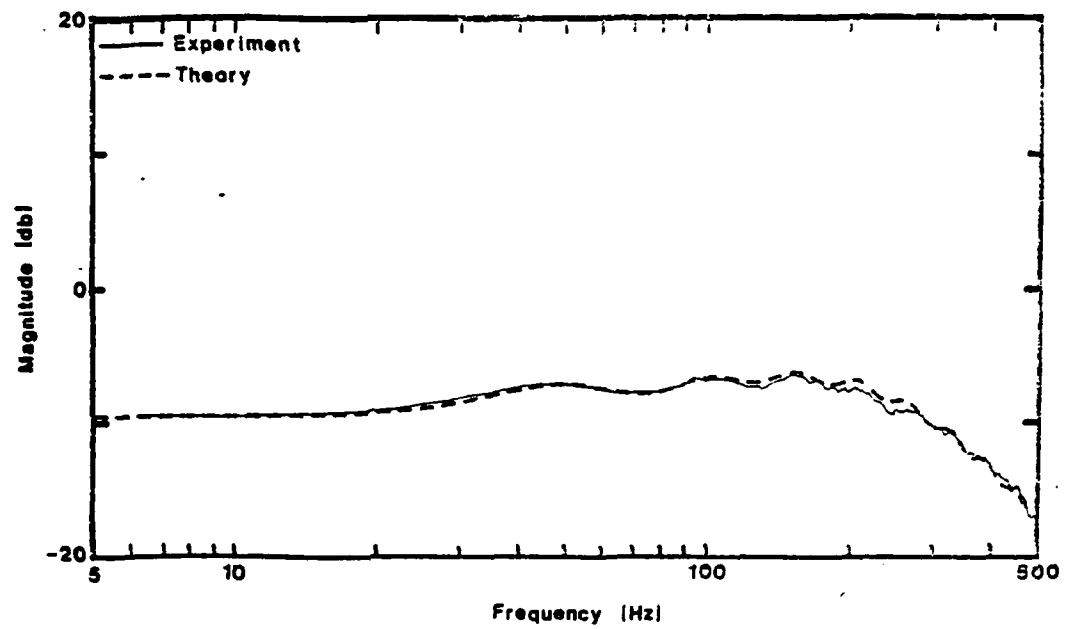
Data Set 124. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



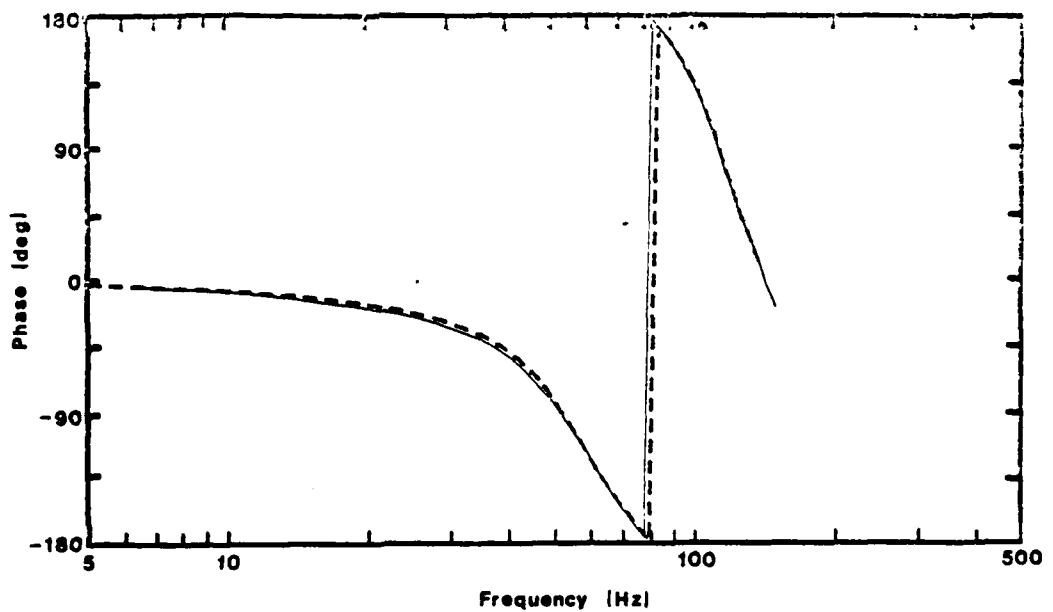
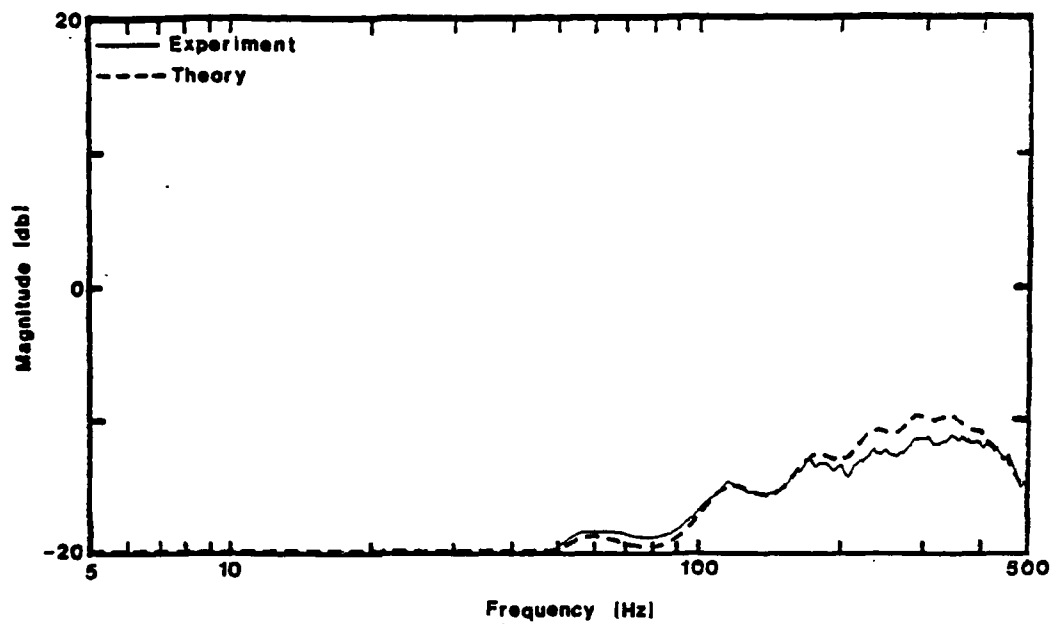
Data Set 125. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



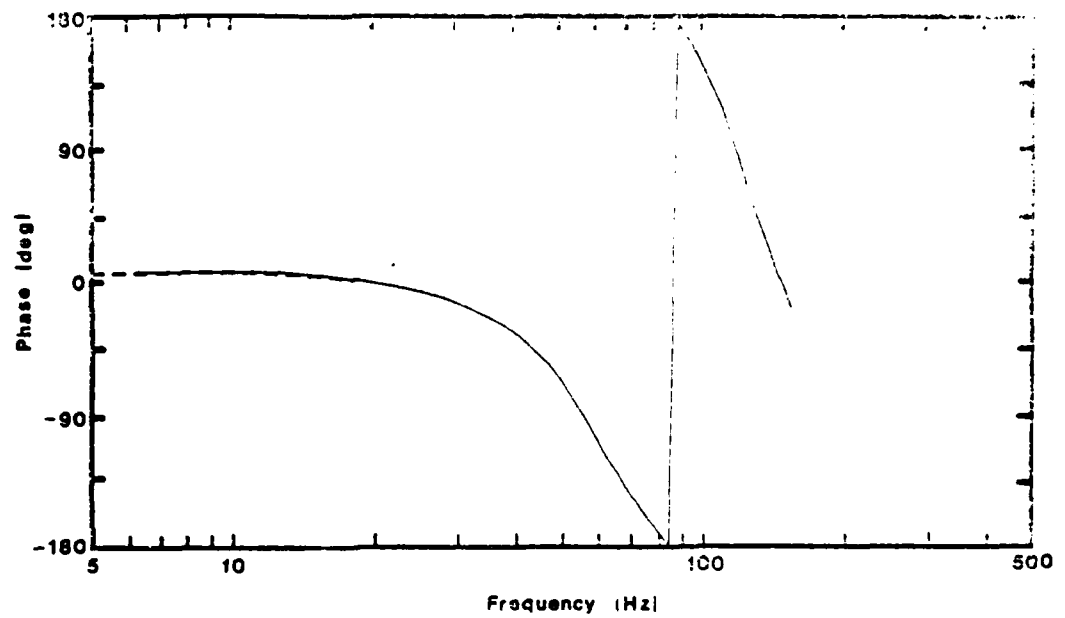
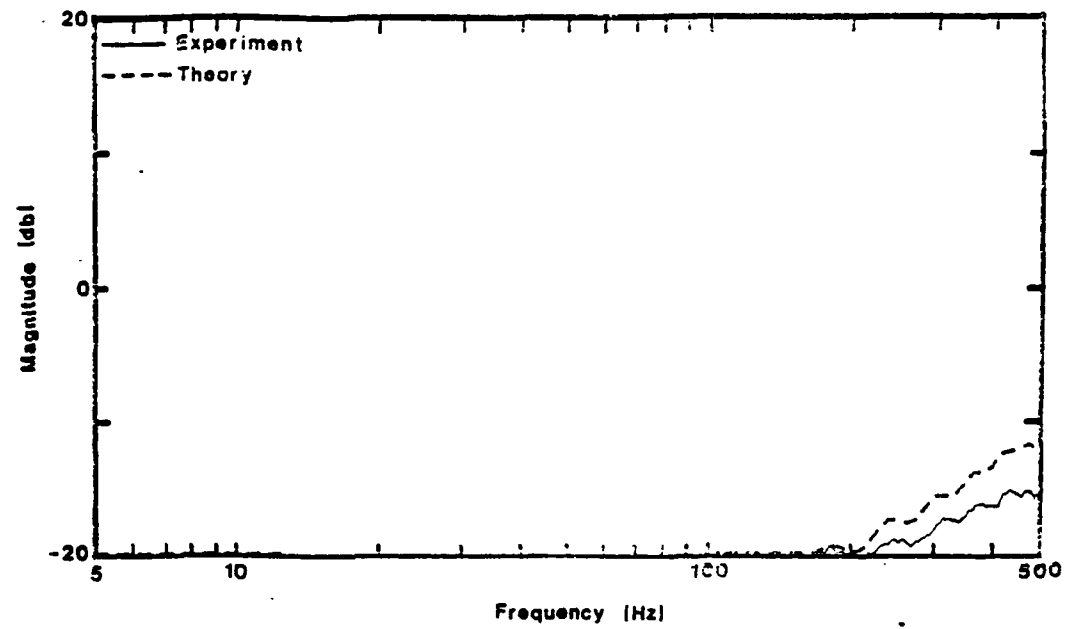
Data Set 126. Line with Source Impedance and Load Impedance  
 ( $l = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #1,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $l = 50$  mm,  $d = .716$  mm)



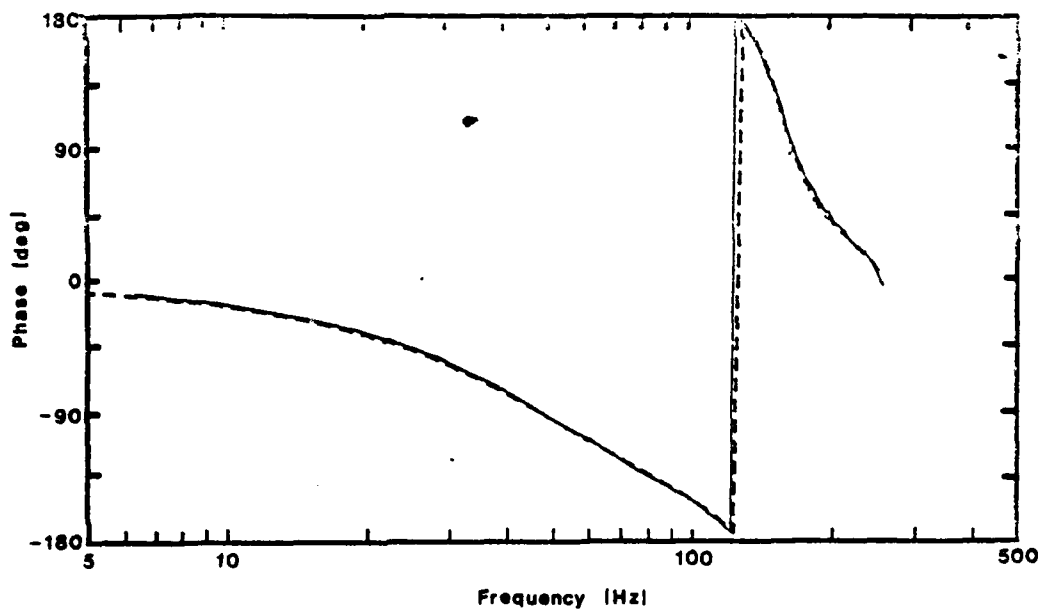
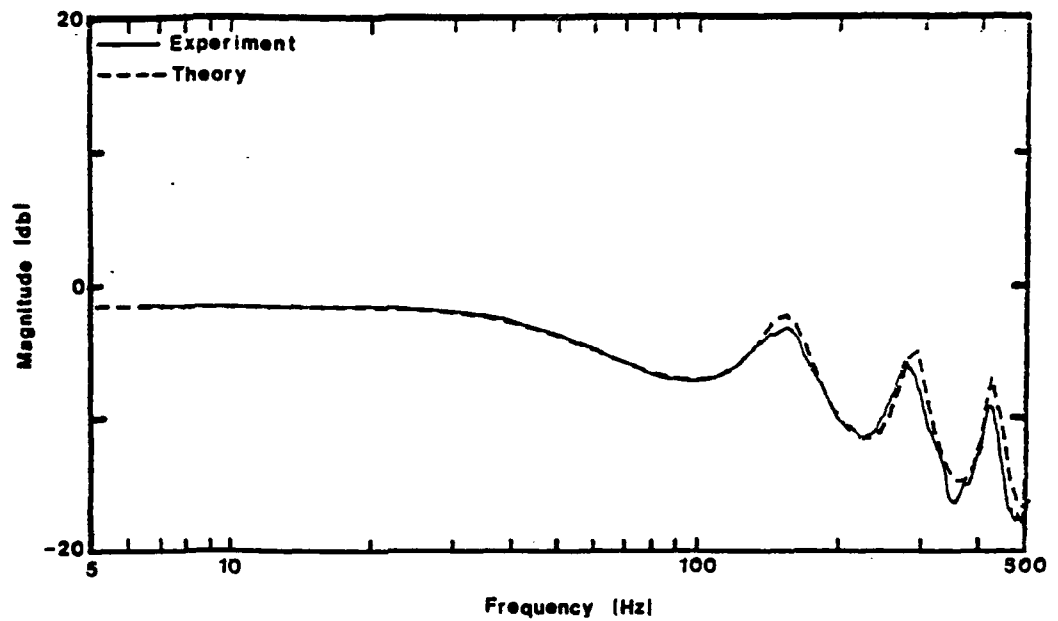
Data Set 127. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



Data Set 128. Line with Source Impedance and Load Impedance  
( $\ell = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



Data Set 129. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 1.7$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



Data Set 130. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$ ; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)

AD-A134 484

FREQUENCY RESPONSE OF HYDRAULIC TRANSMISSION LINES(U)  
TEXAS UNIV AT ARLINGTON FLUID CONTROLS CENTER FOR  
RESEARCH AND DEVELOPMENT R L WOODS ET AL. 25 MAY 82

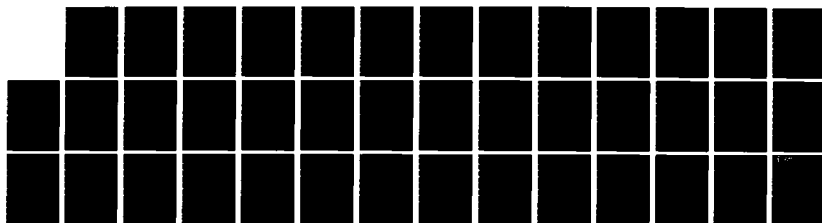
3/3

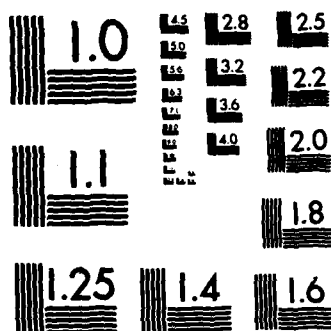
UNCLASSIFIED

NADC-80252-60 N62669-81-M-3056

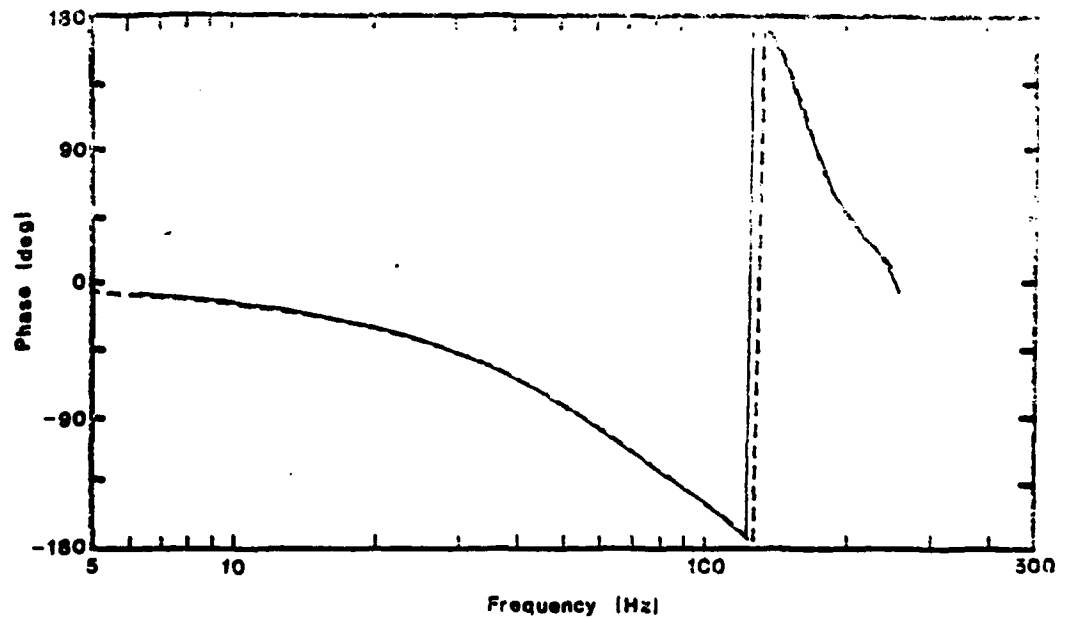
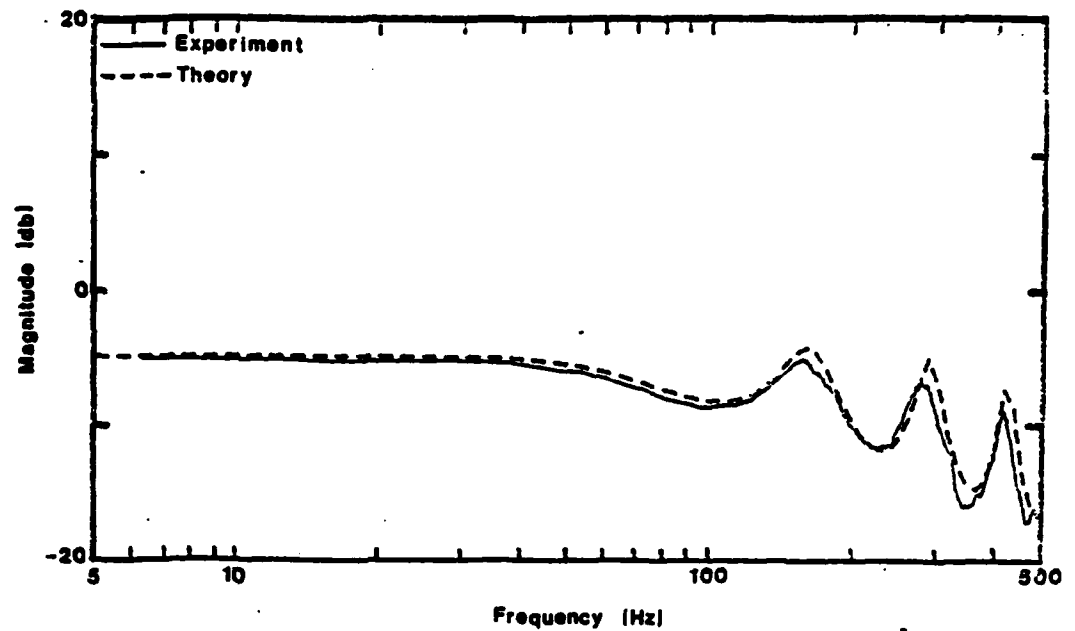
F/G 1/3

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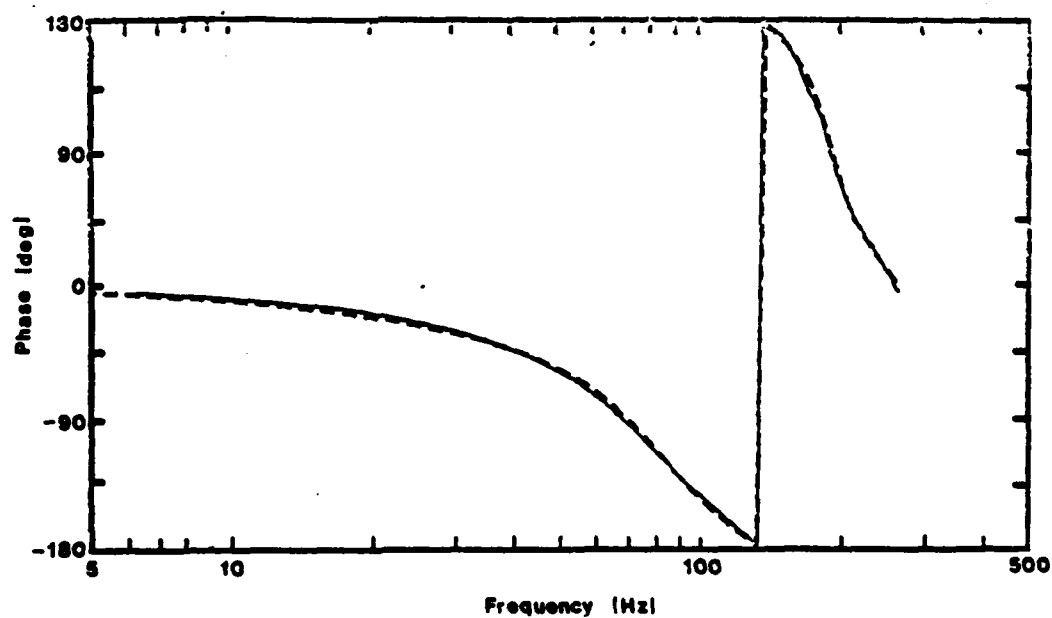
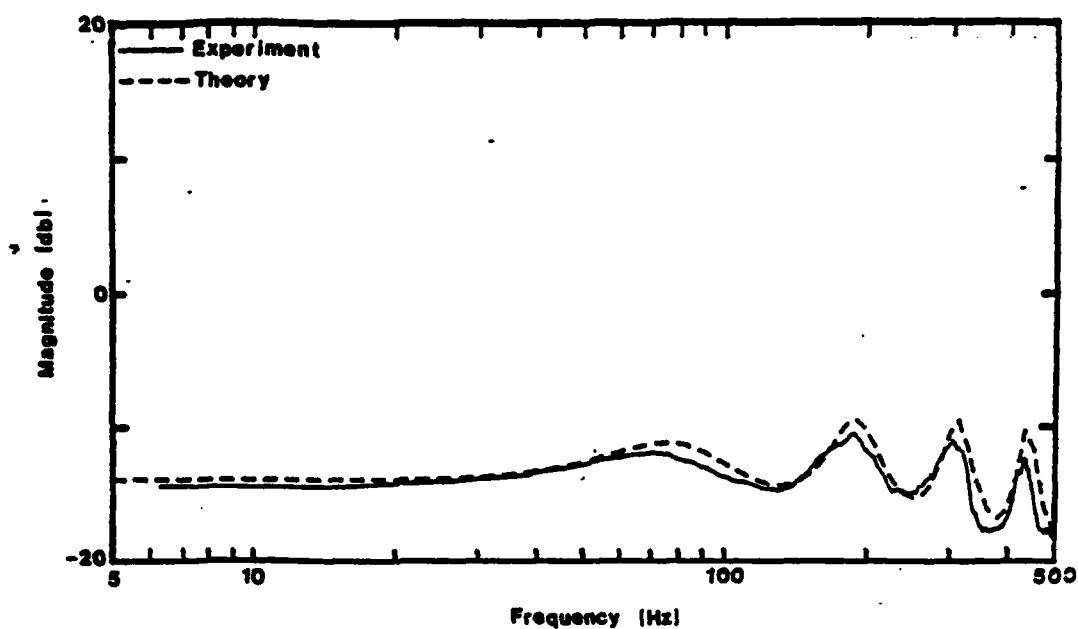




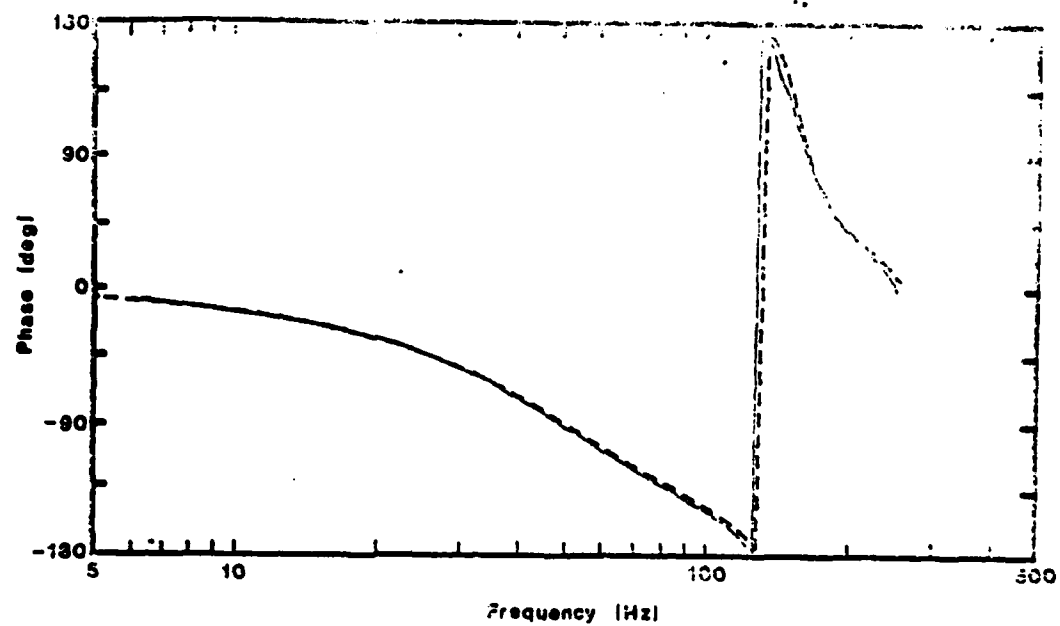
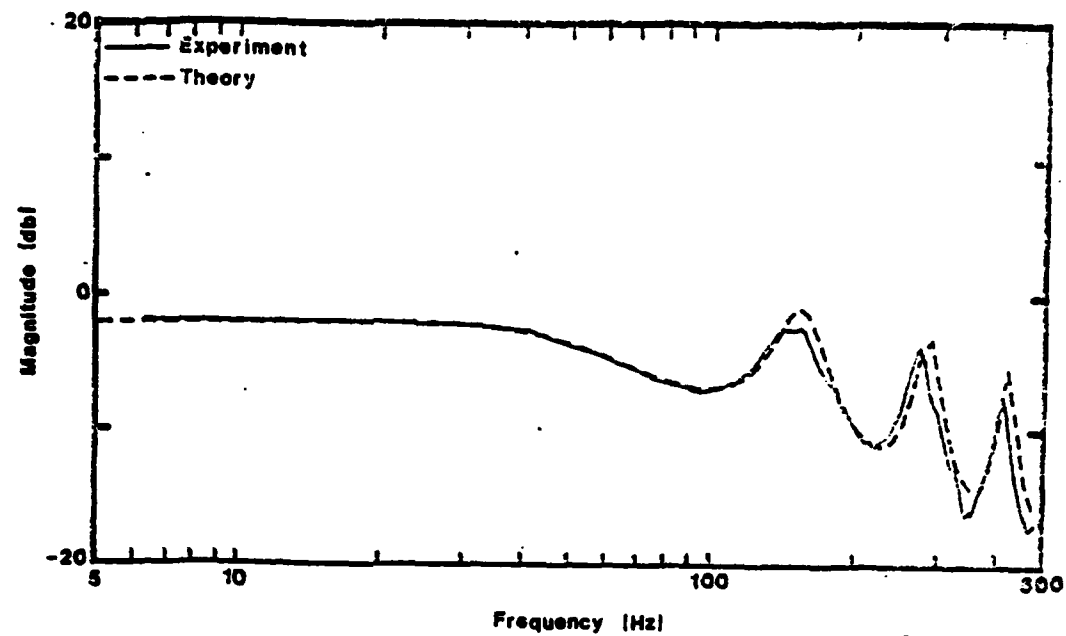
MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A



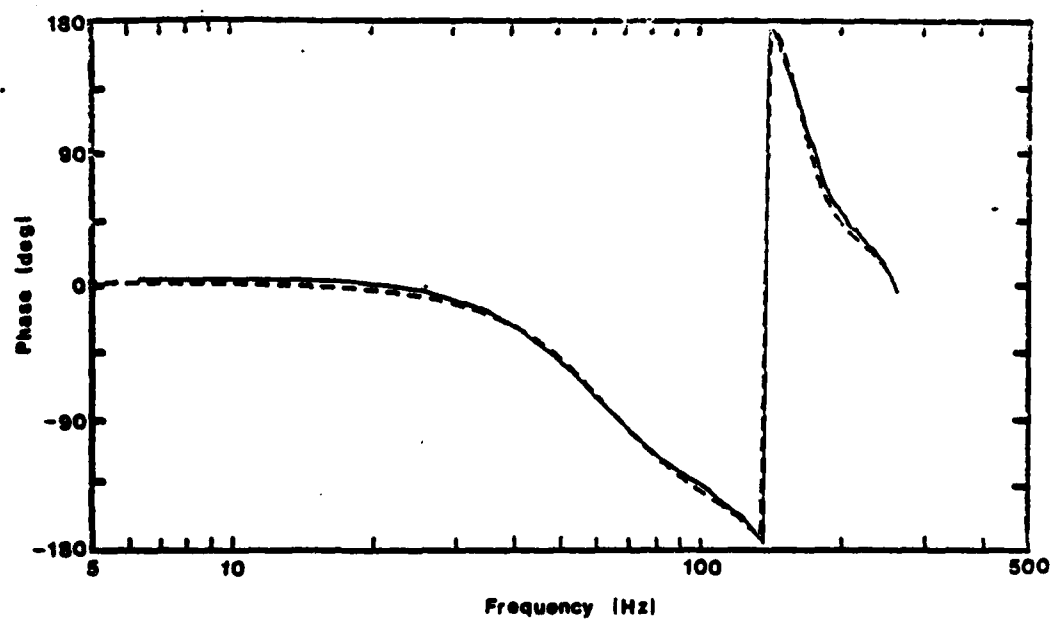
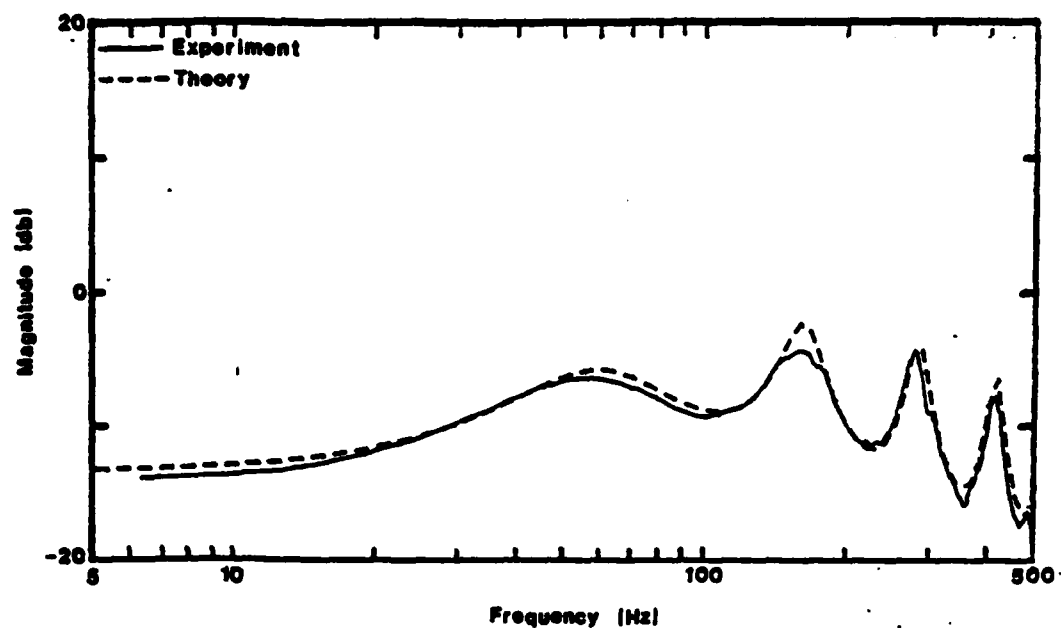
Data Set 131. Line with Source Impedance and Load Impedance  
( $\lambda = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



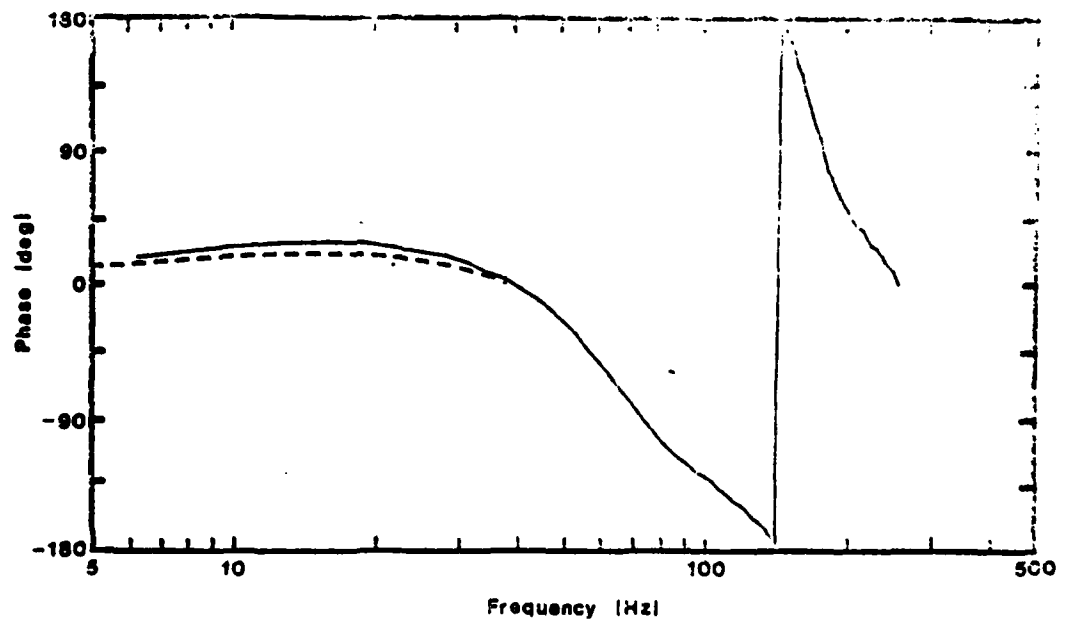
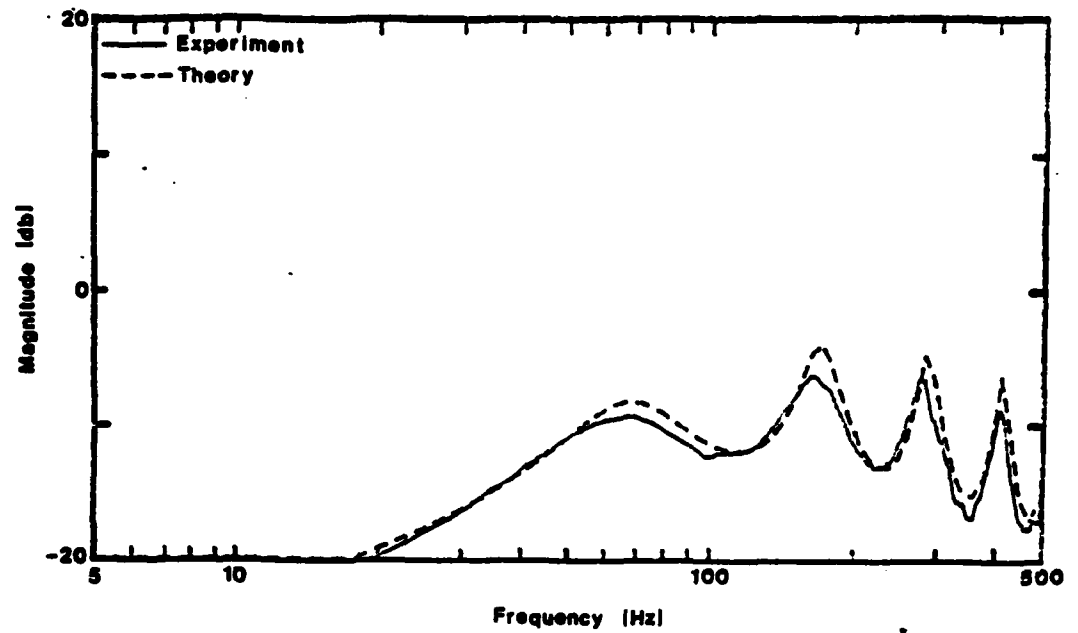
Data Set 132. Line with Source Impedance and Load Impedance  
 ( $l = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $l = 53$  mm,  
 $d = .716$ ; Load: Resistor #5, 4 tubes,  $l = 52$  mm,  $d = .716$  mm)



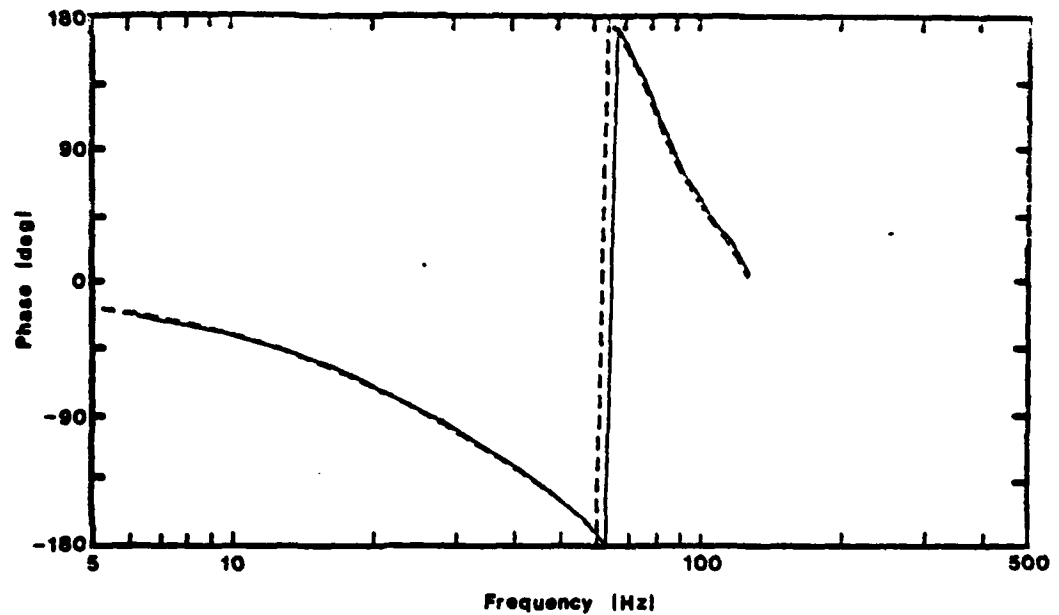
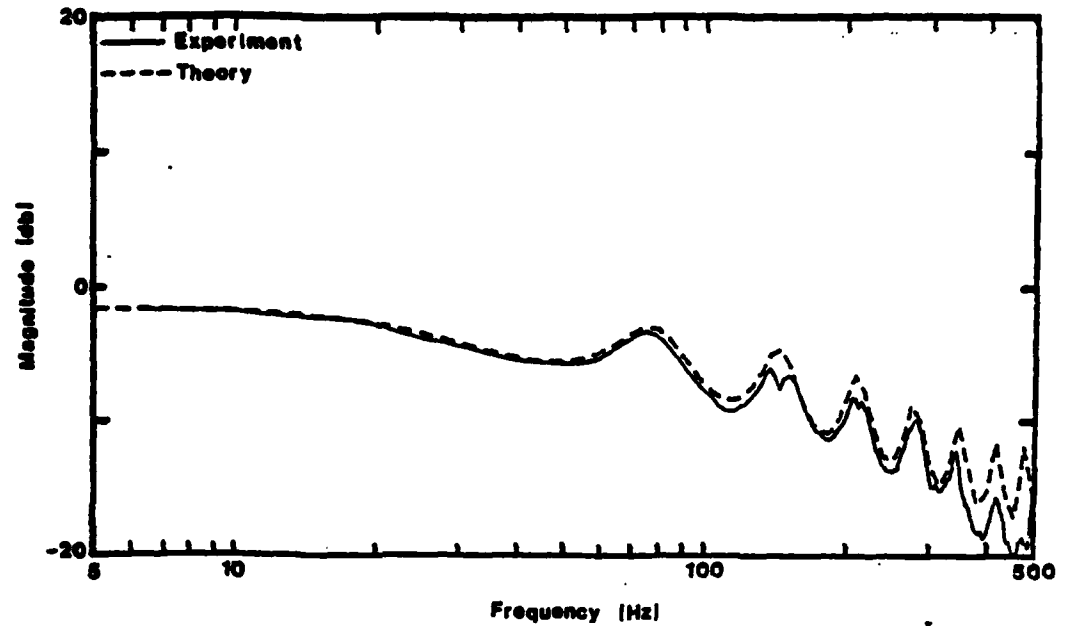
Data Set 133. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



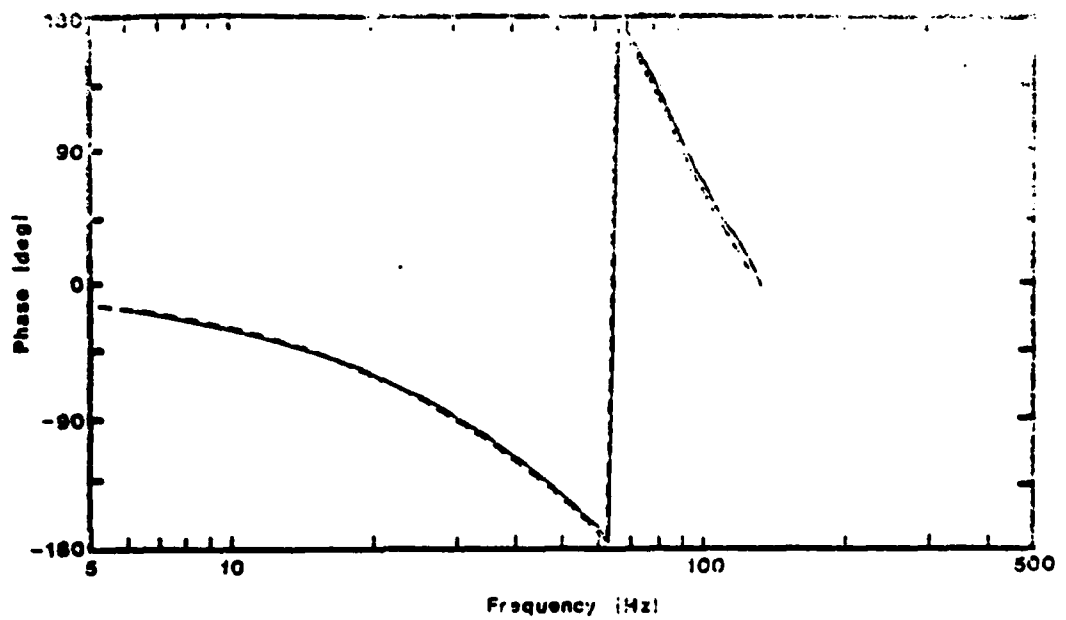
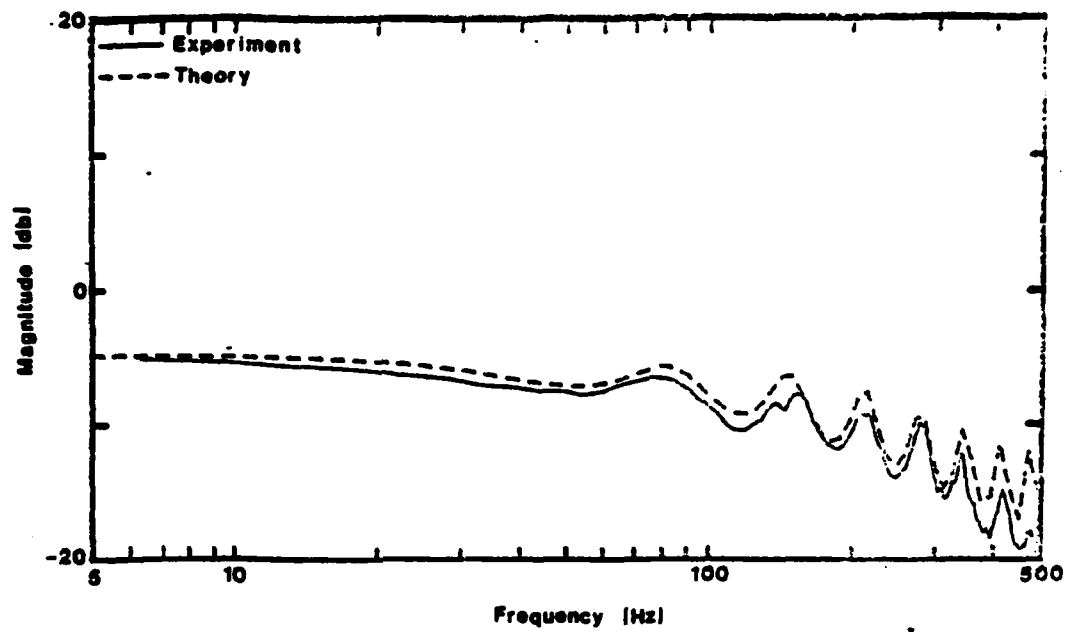
Data Set 134. Line with Source Impedance and Load Impedance  
 ( $l = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $l = 290$  mm,  $d = 1.63$  mm)



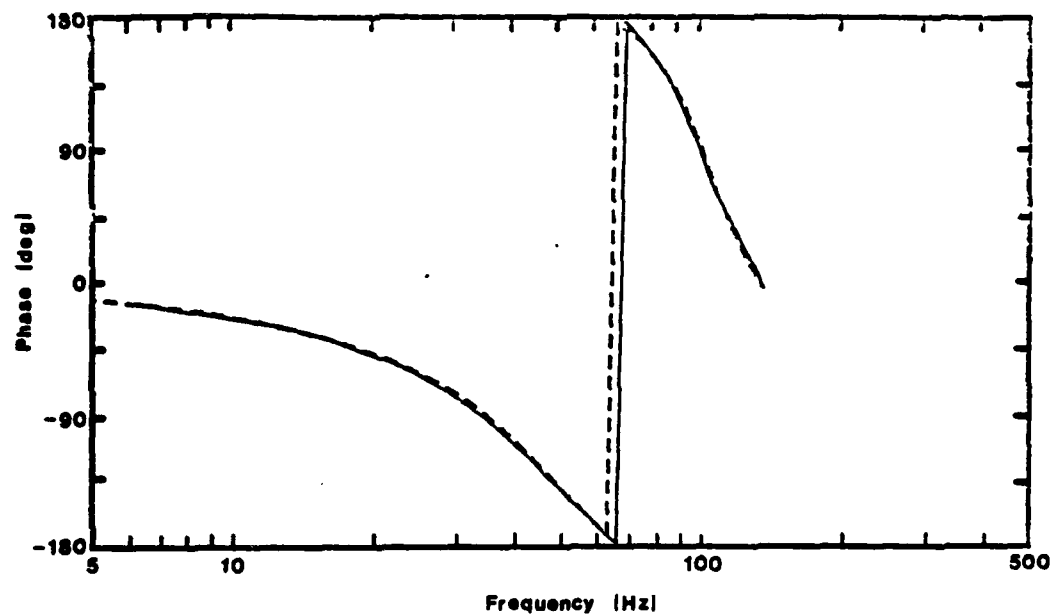
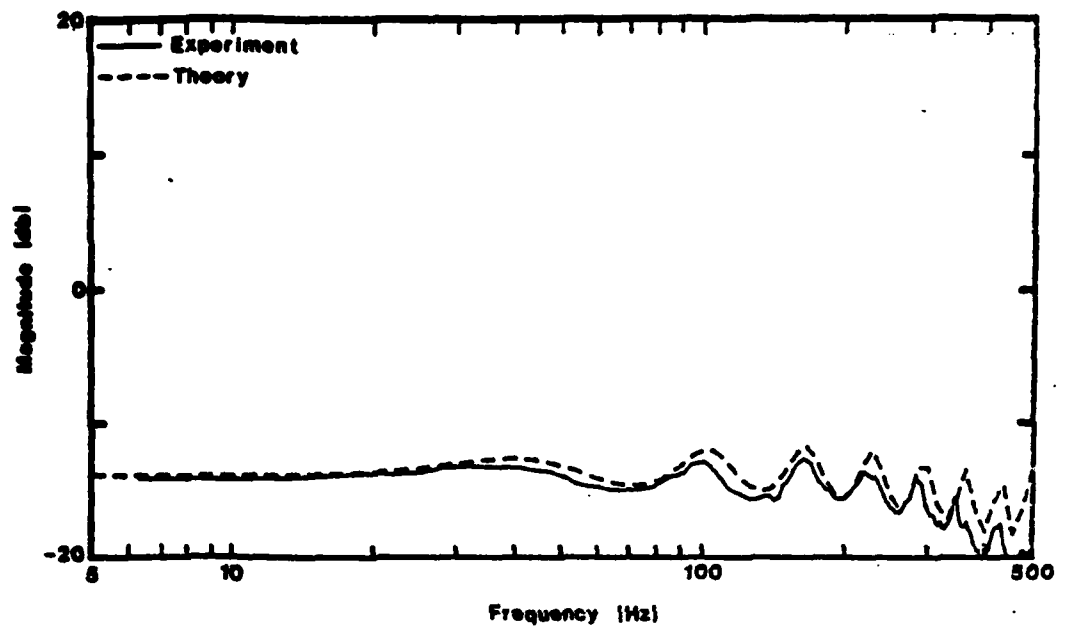
Data Set 135. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



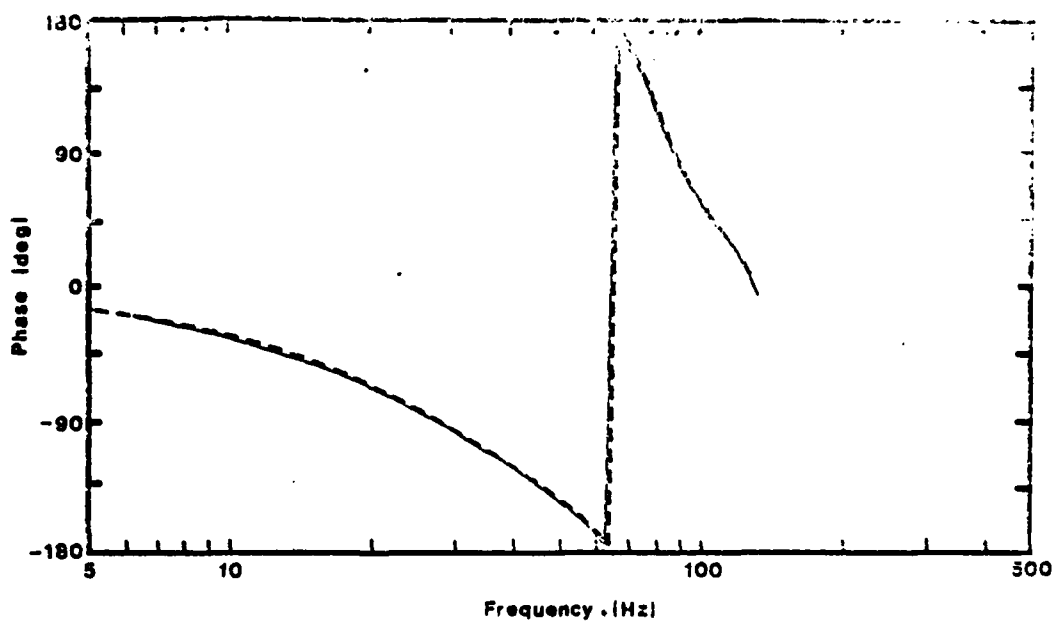
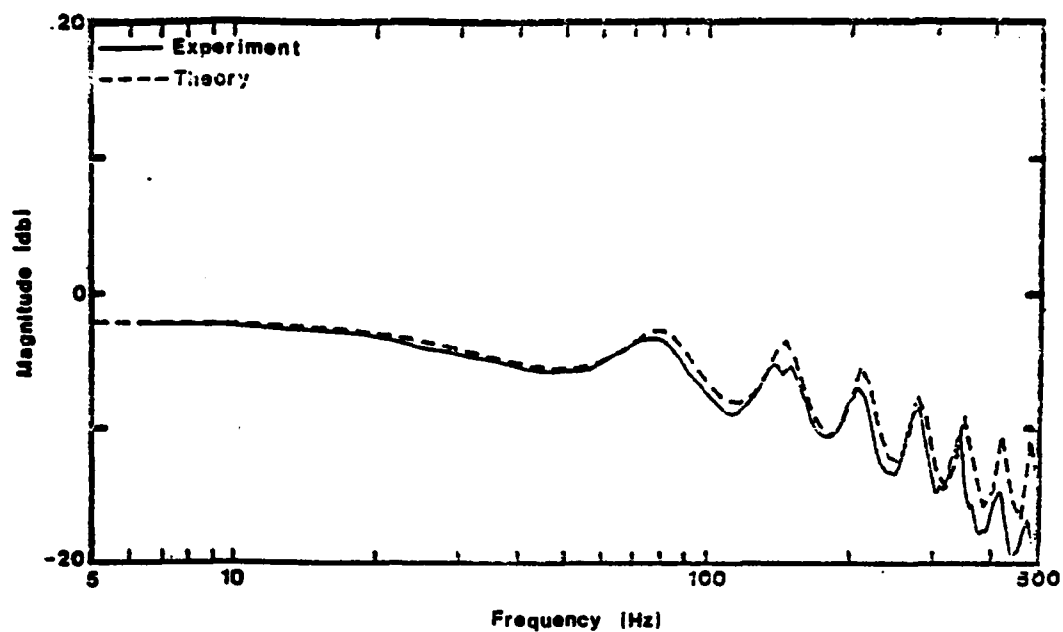
Data Set 136. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



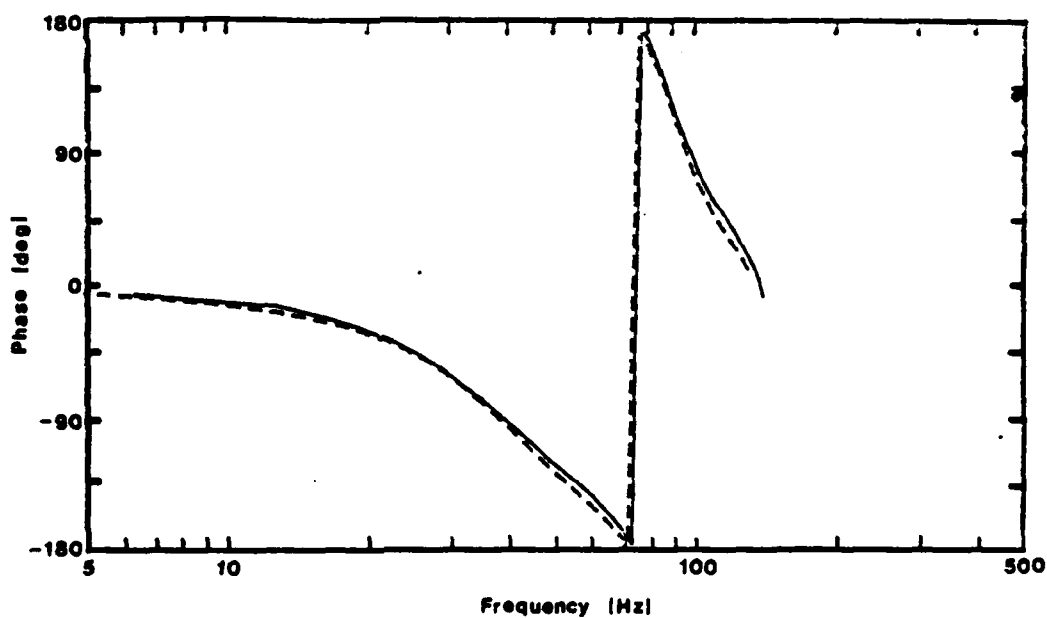
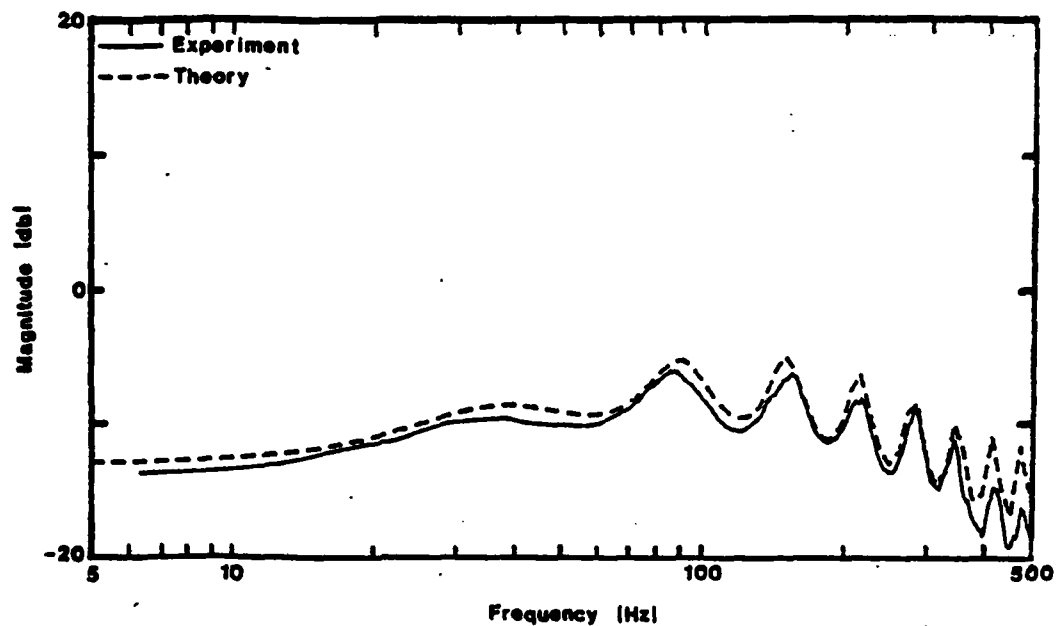
Data Set 137. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\lambda = 50$  mm,  $d = .716$  mm)



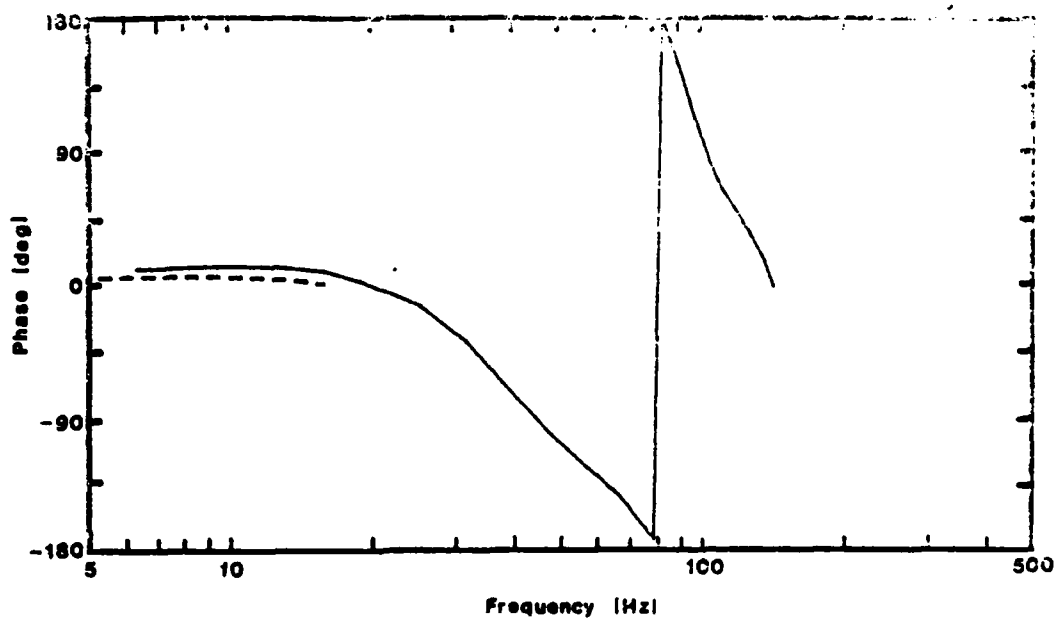
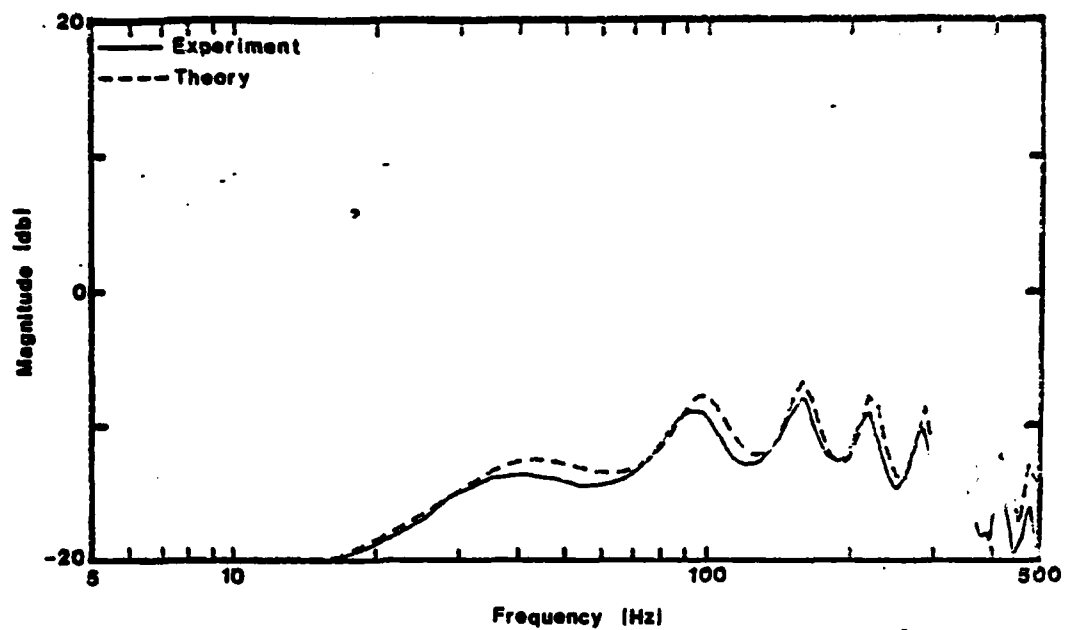
Data Set 138. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



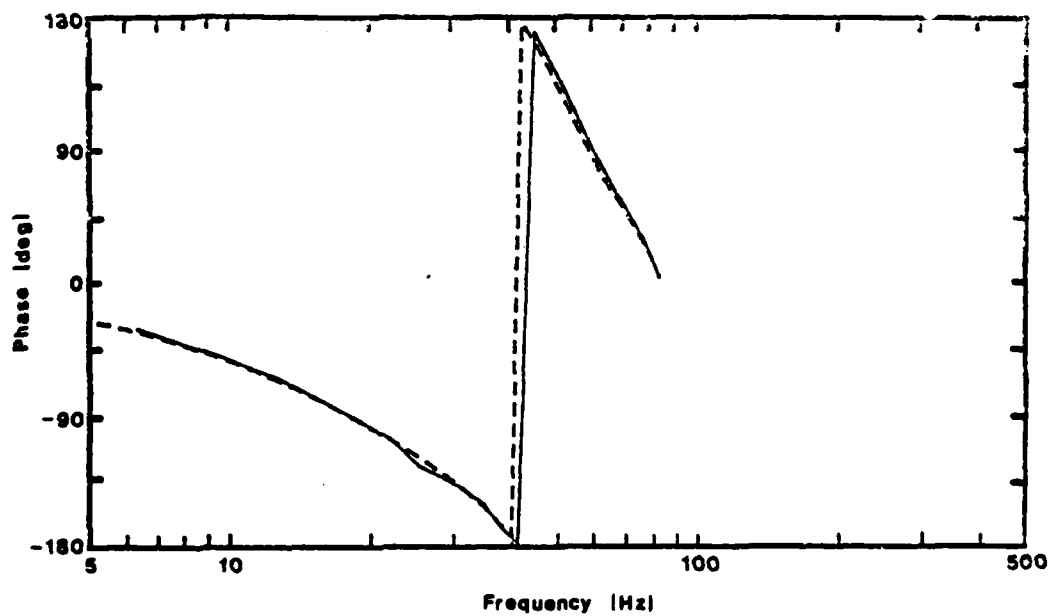
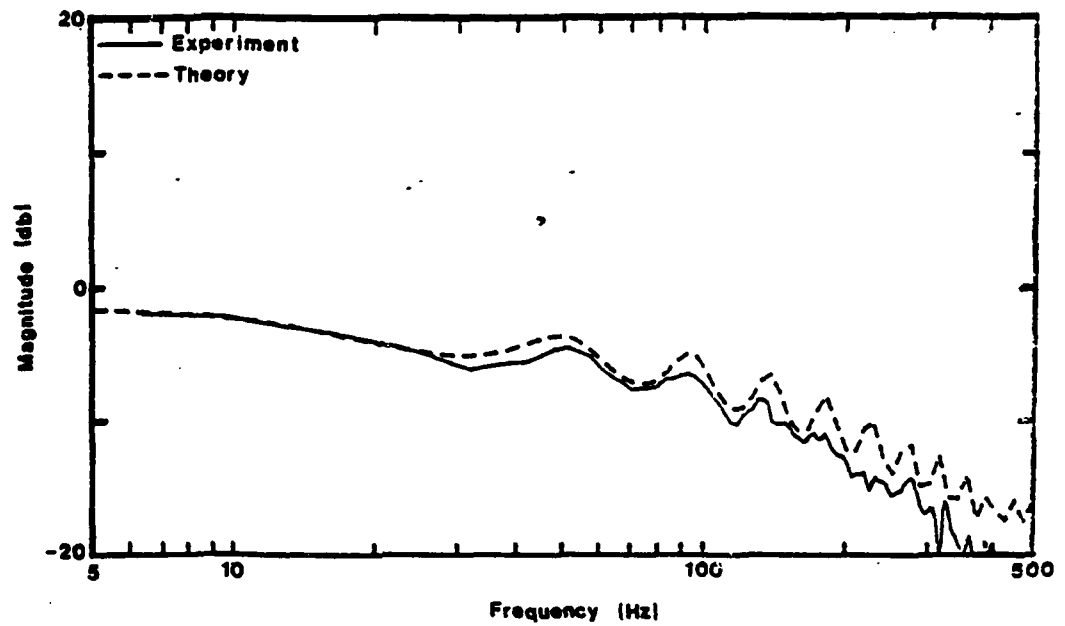
Data Set 139. Line with Source Impedance and Load Impedance  
( $\lambda = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



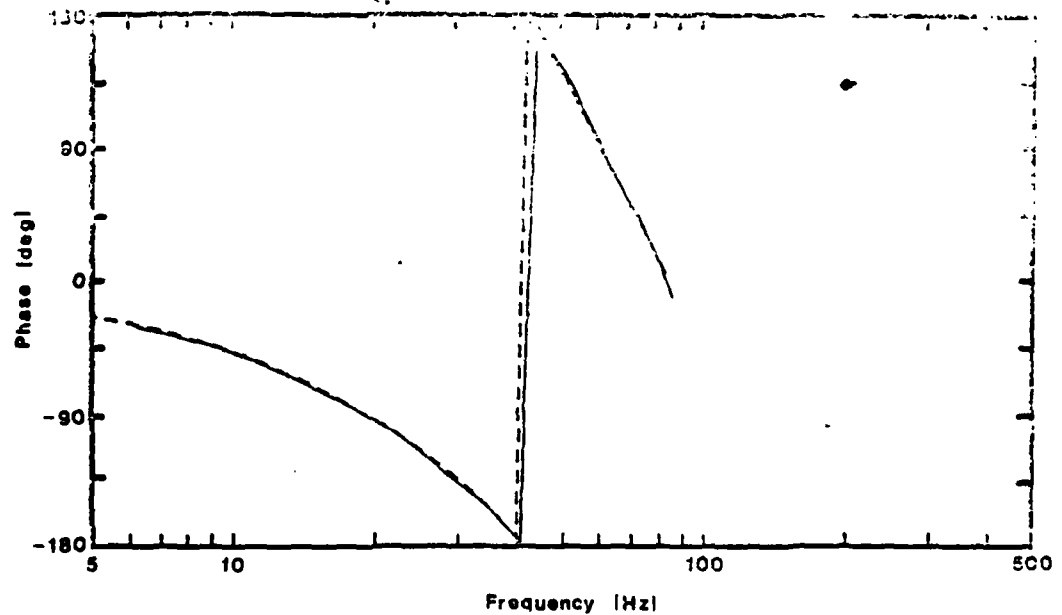
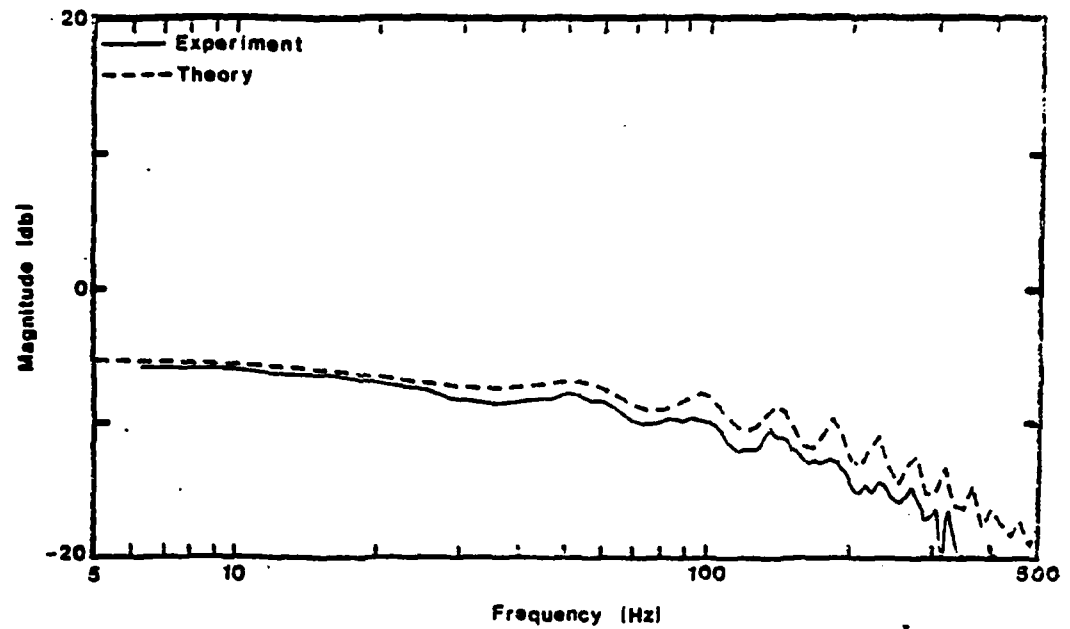
Data Set 140. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



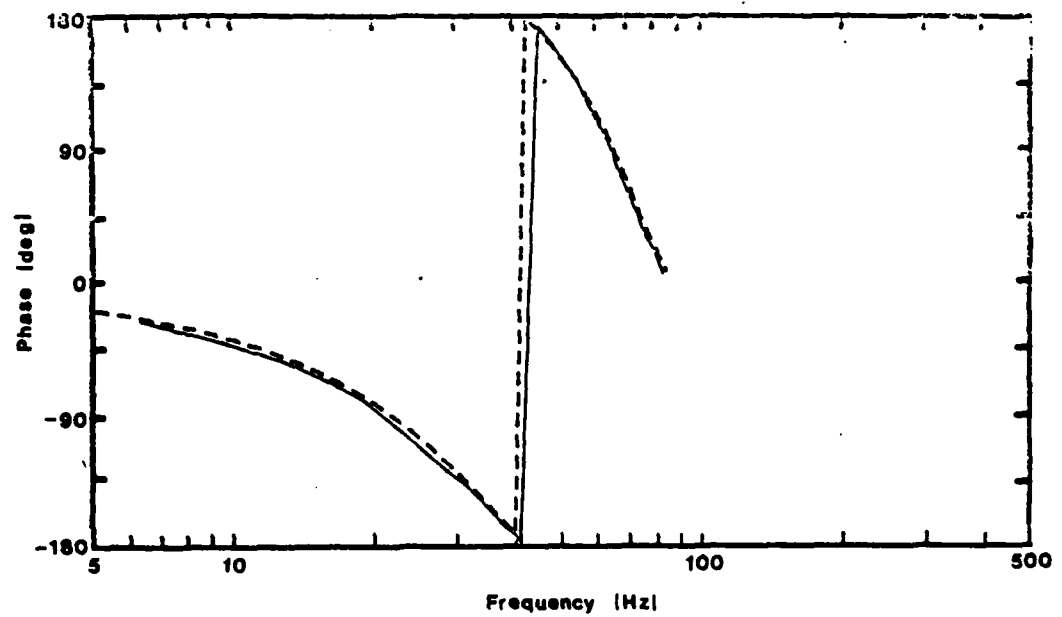
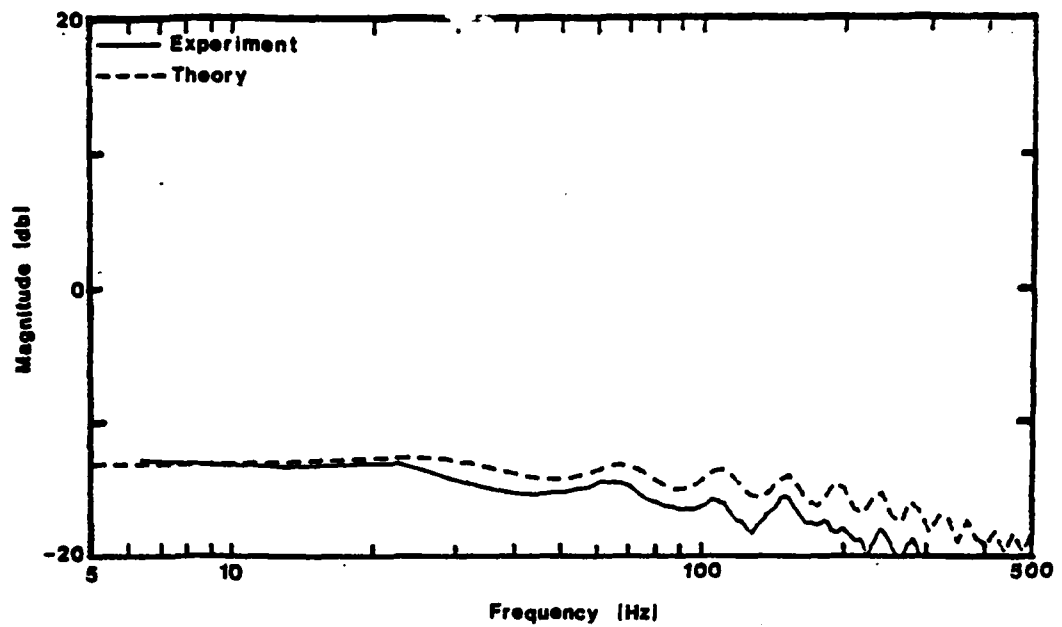
Data Set 141. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = 716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



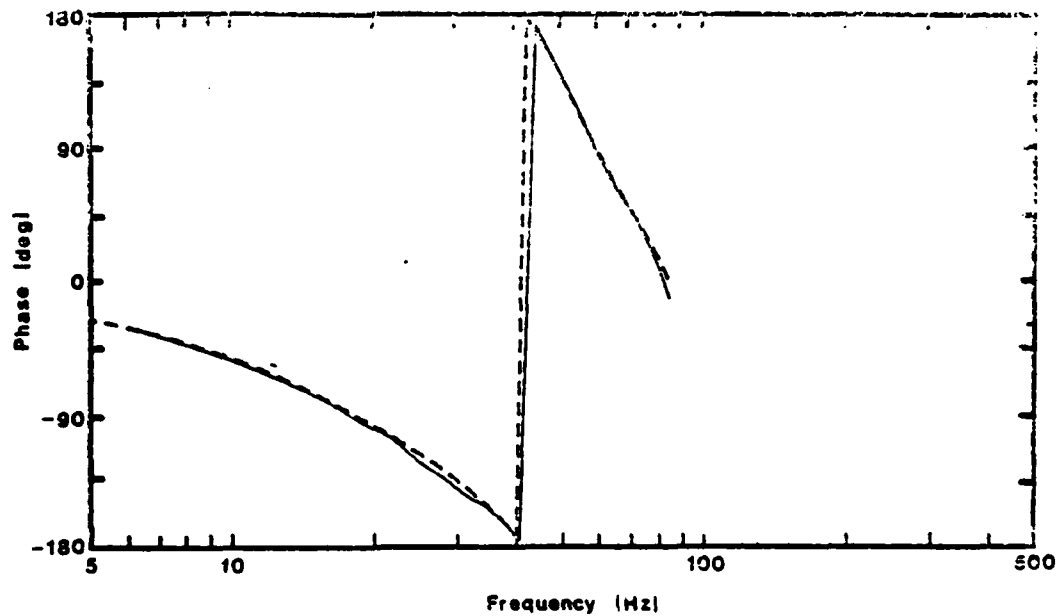
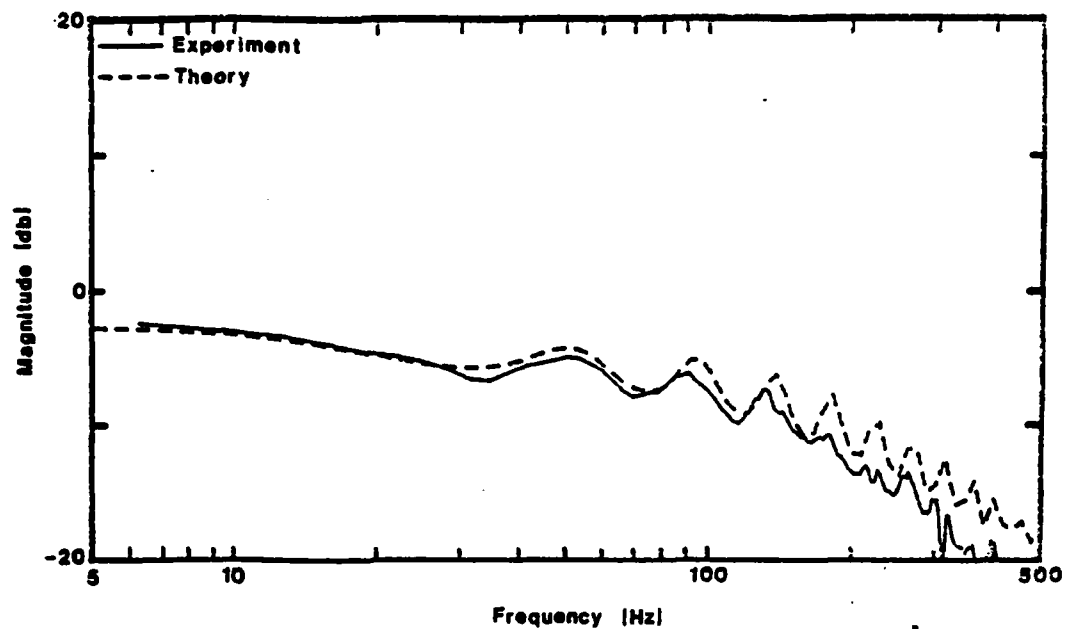
Data Set 142. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



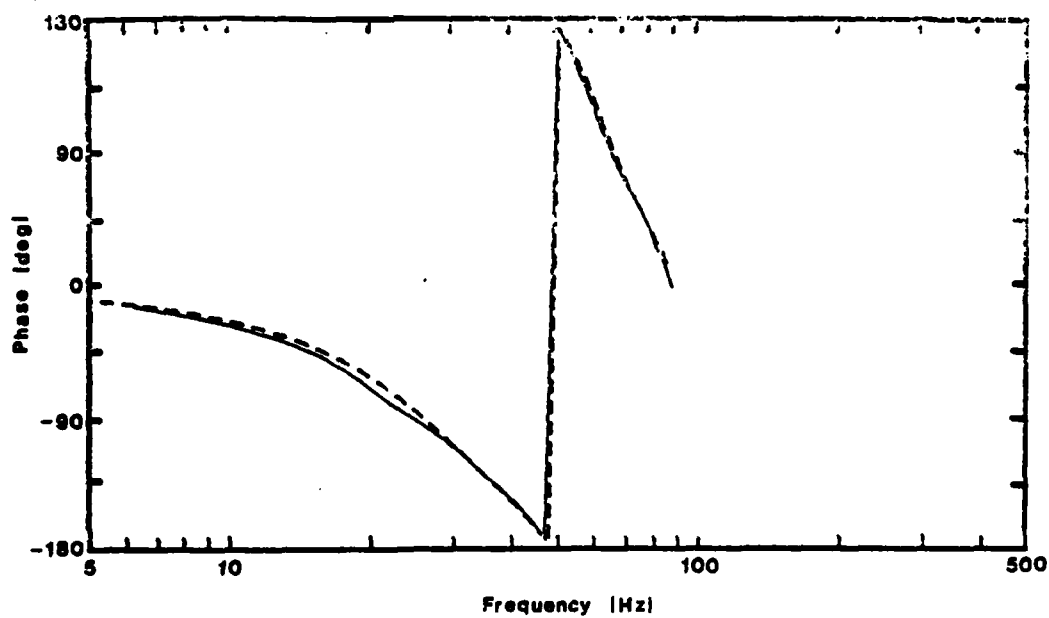
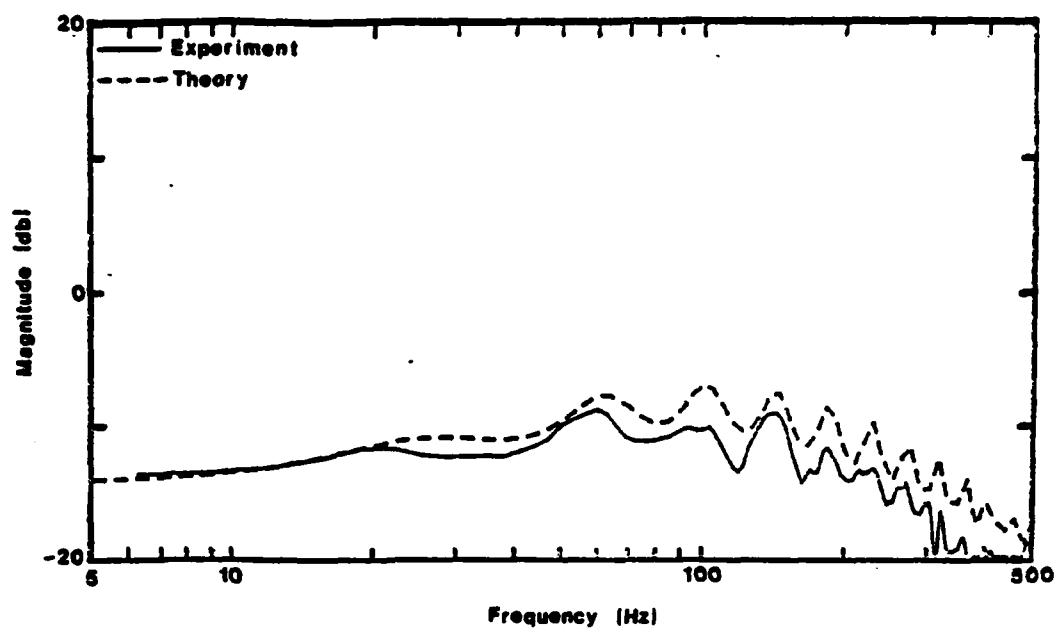
Data Set 143. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



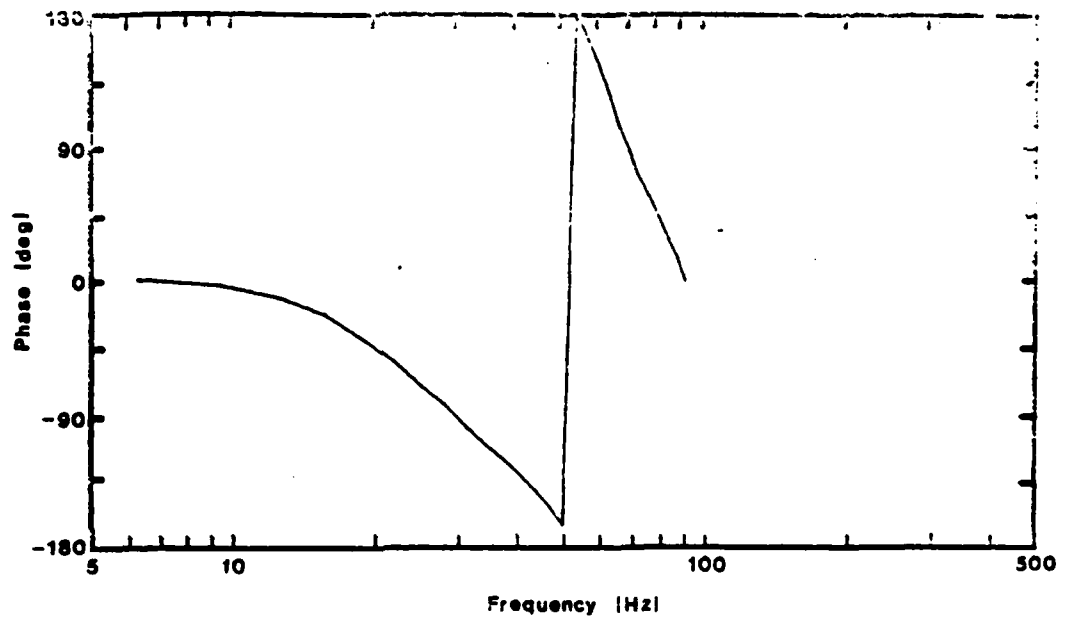
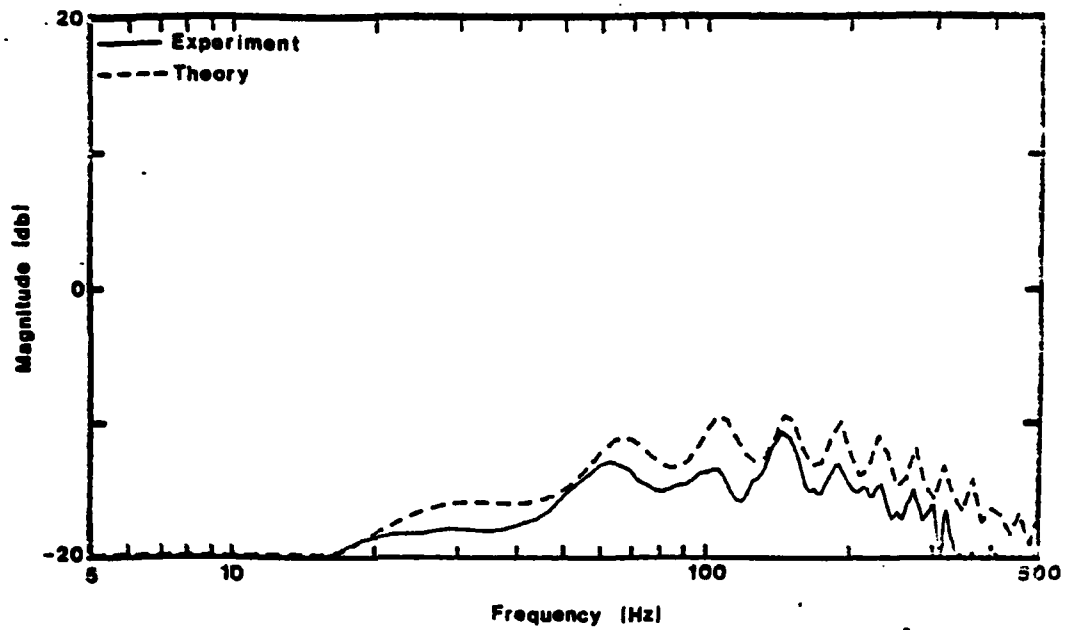
Data Set 144. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



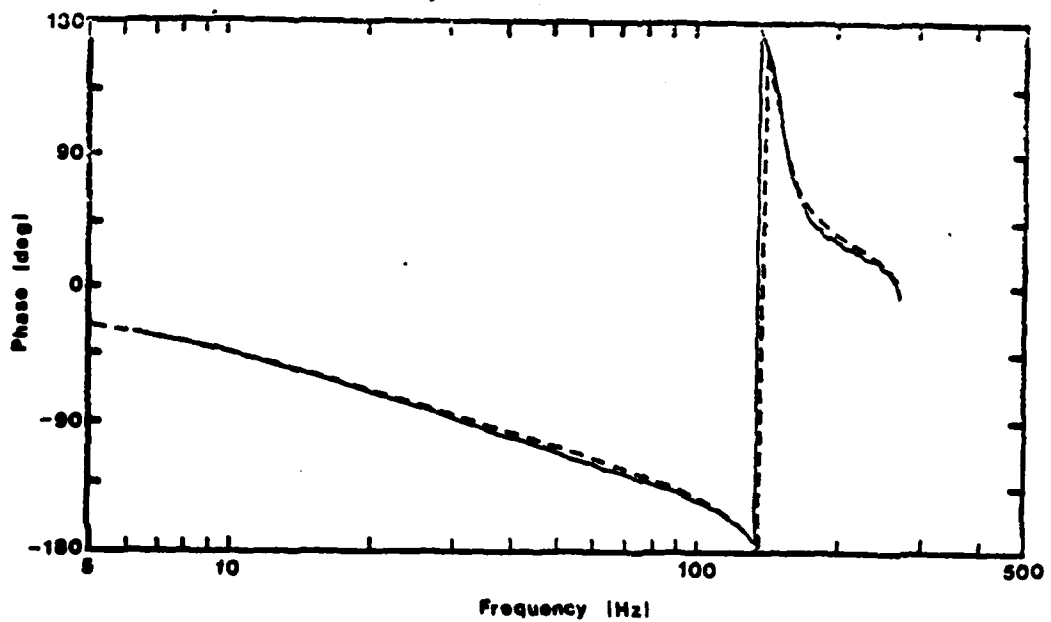
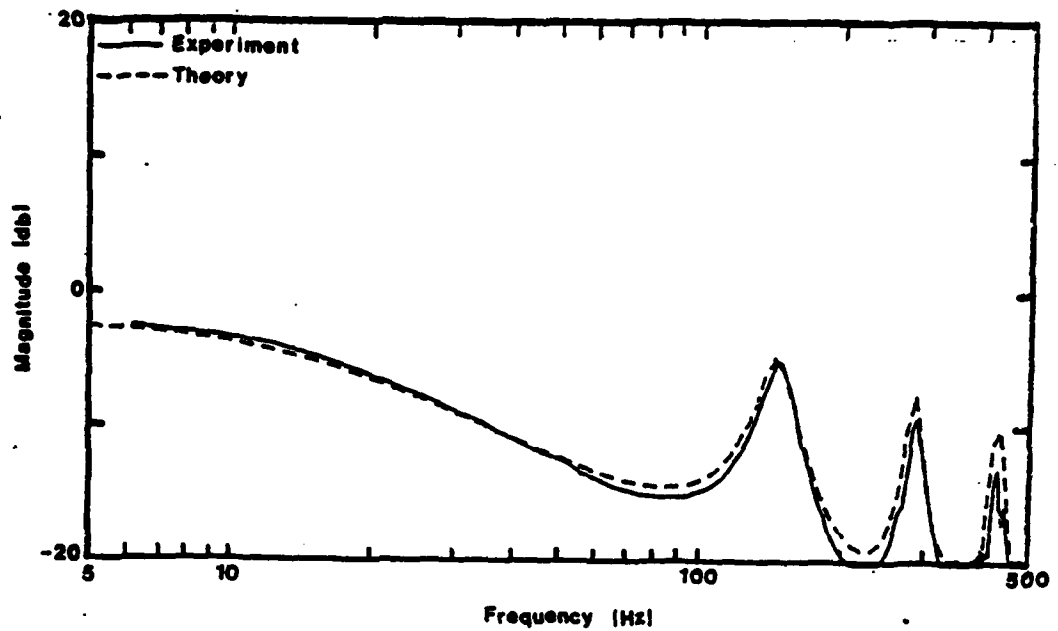
Data Set 145. Line with Source Impedance and Load Impedance  
( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



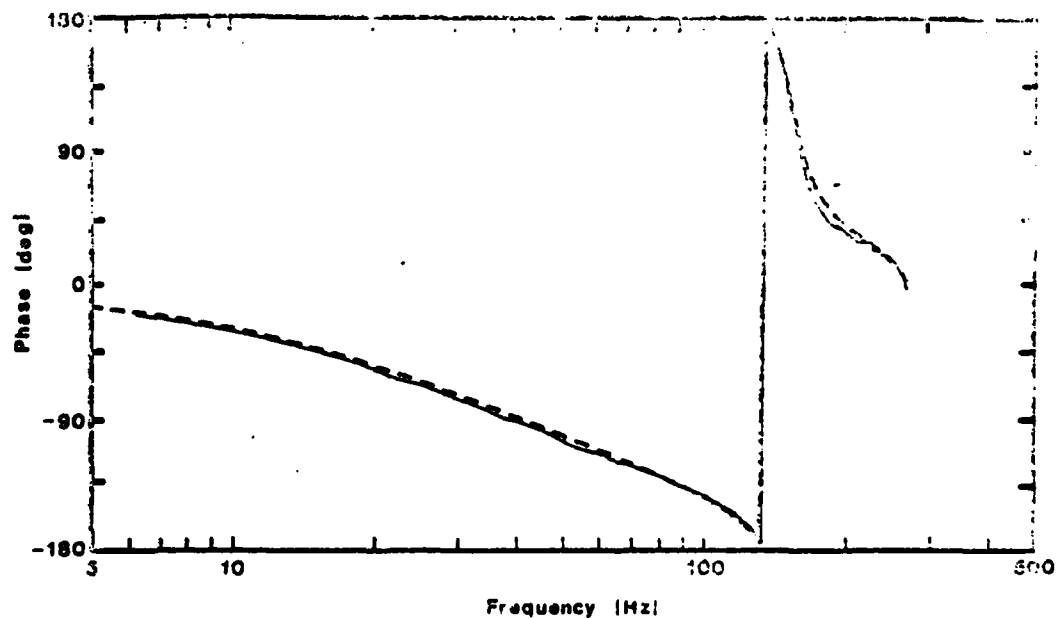
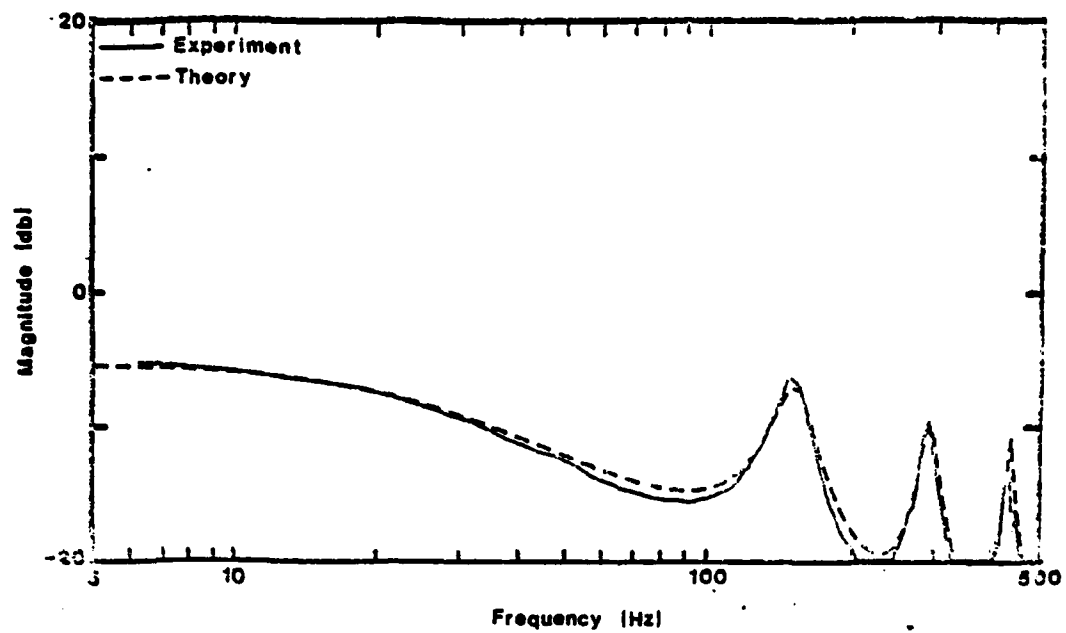
Data Set 146. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



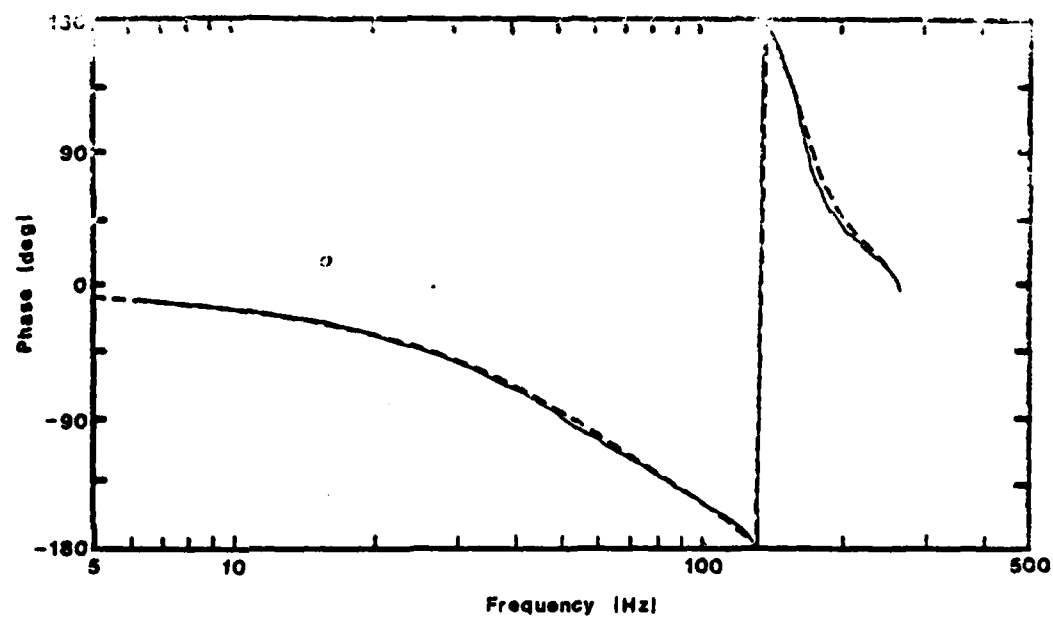
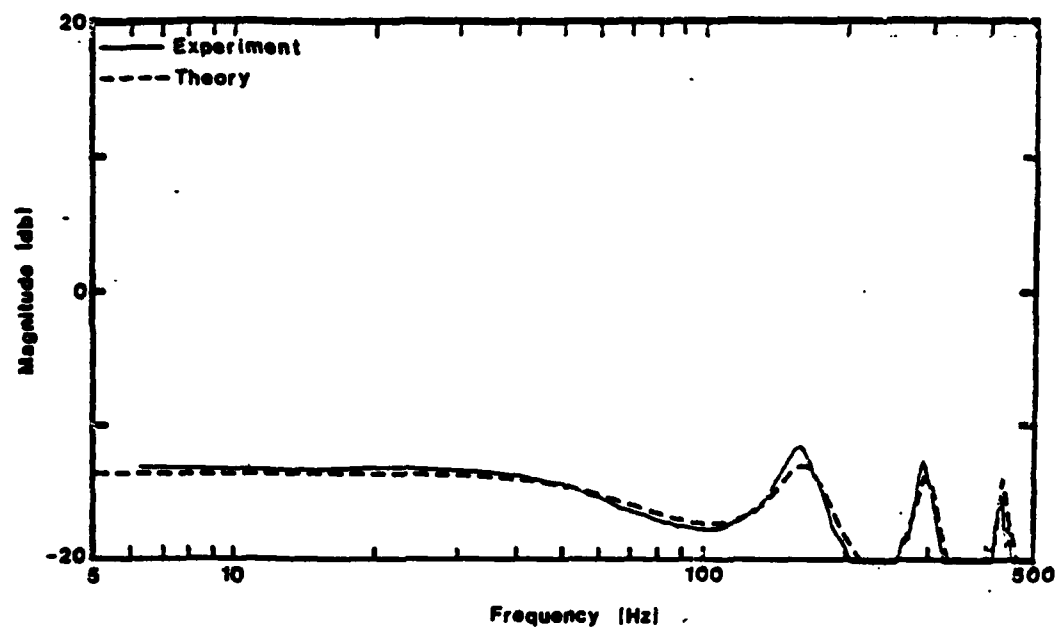
Data Set 147. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 4.8$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



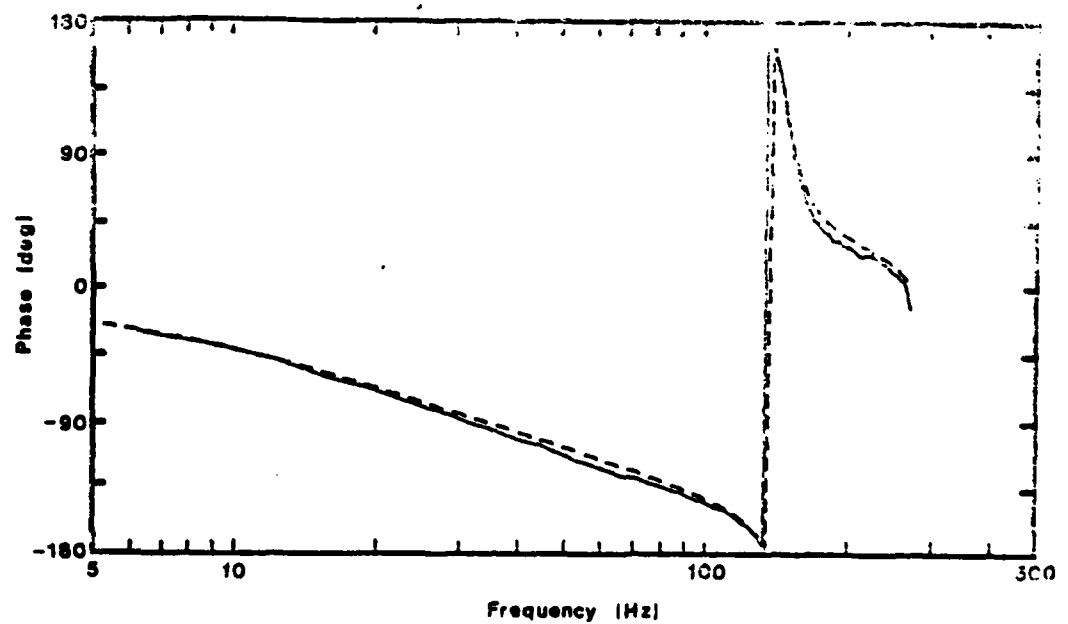
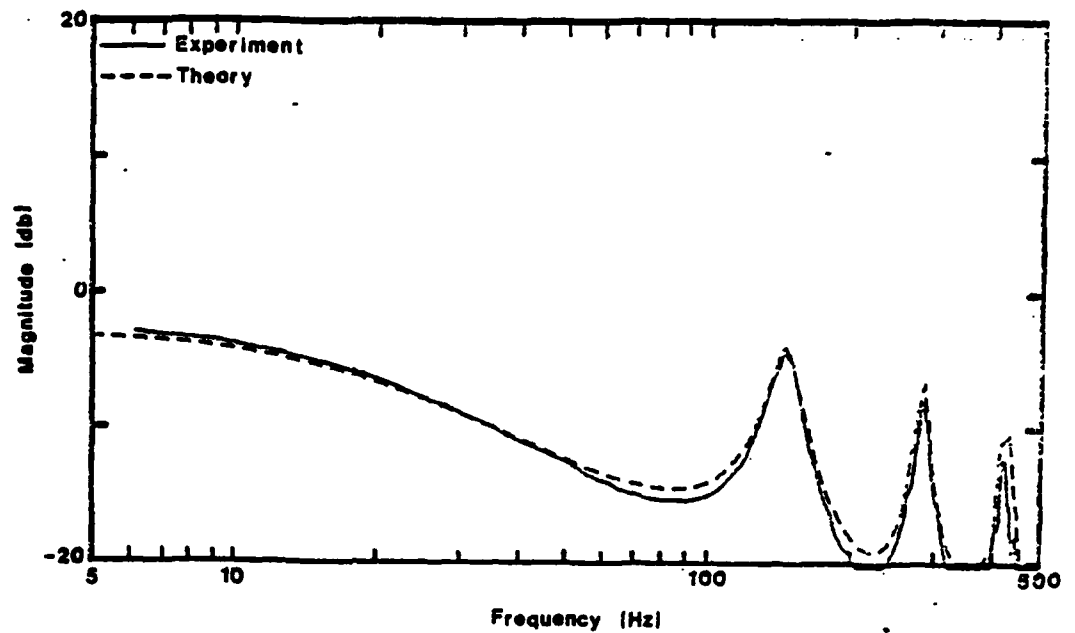
Data Set 148. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



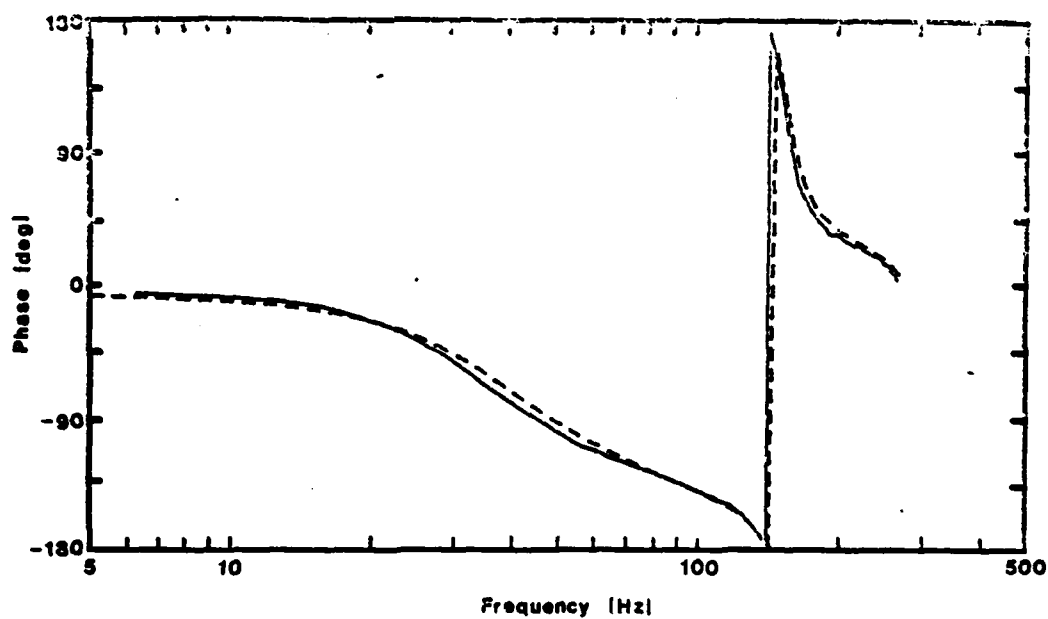
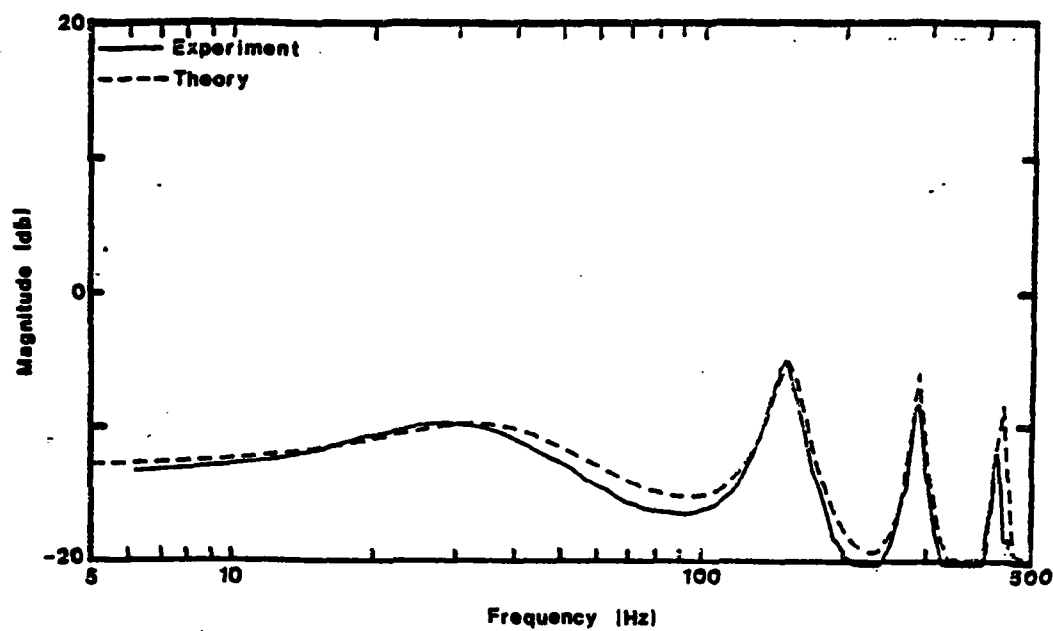
Data Set 149. Line with Source Impedance and Load Impedance  
( $\ell = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



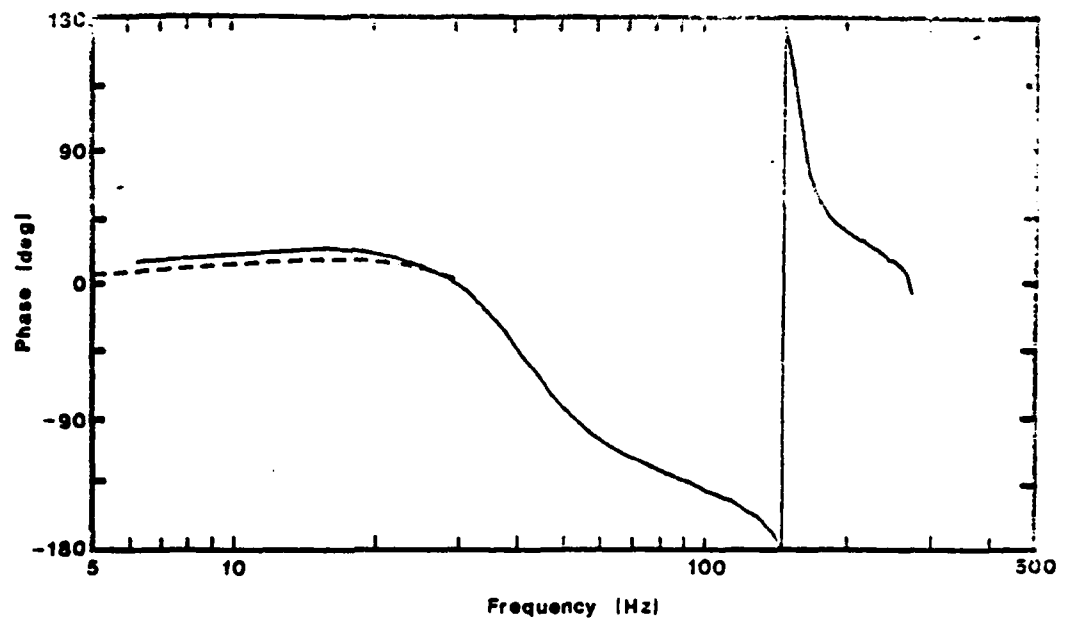
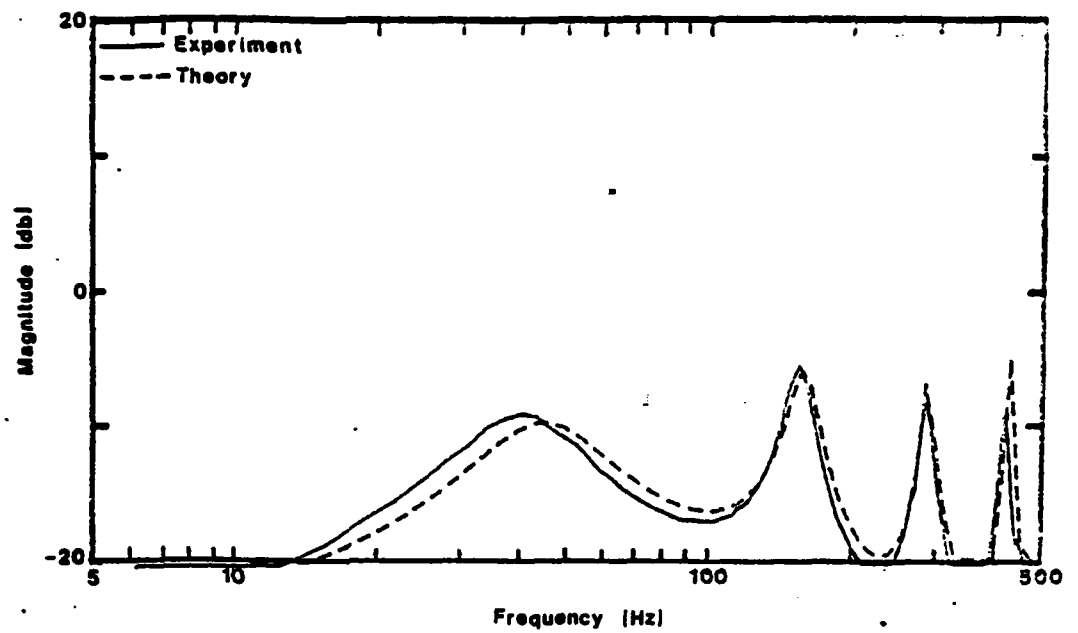
Data Set 150. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



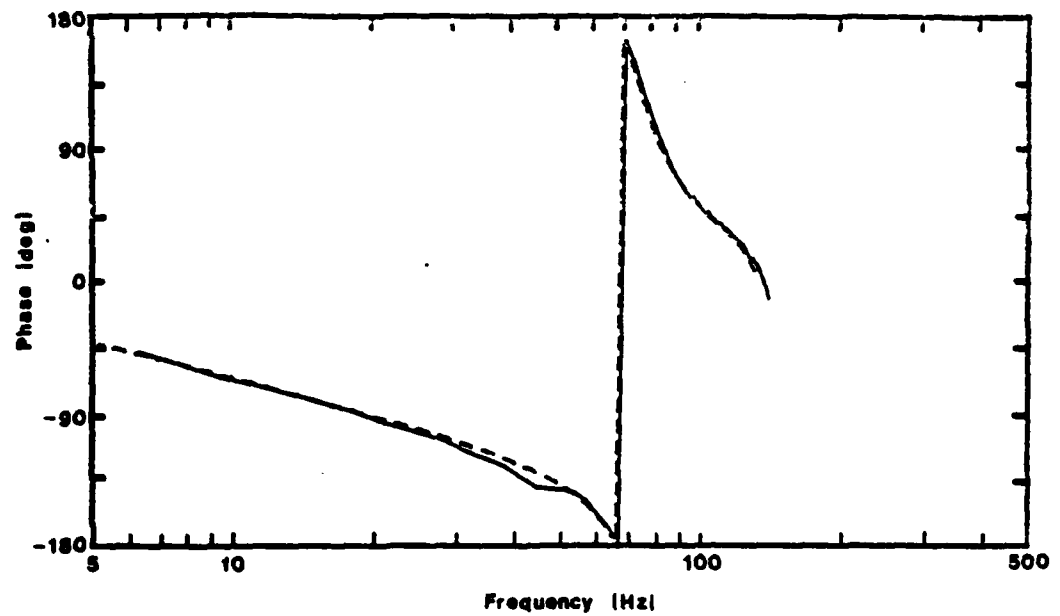
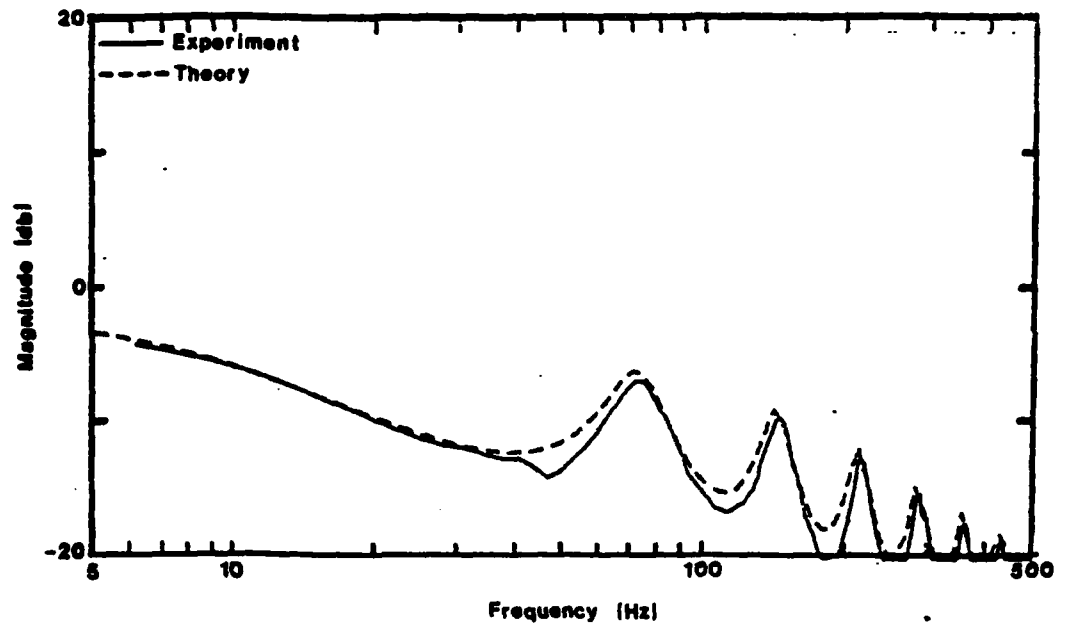
Data Set 151. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\ell = 297$  mm,  $d = .88$  mm)



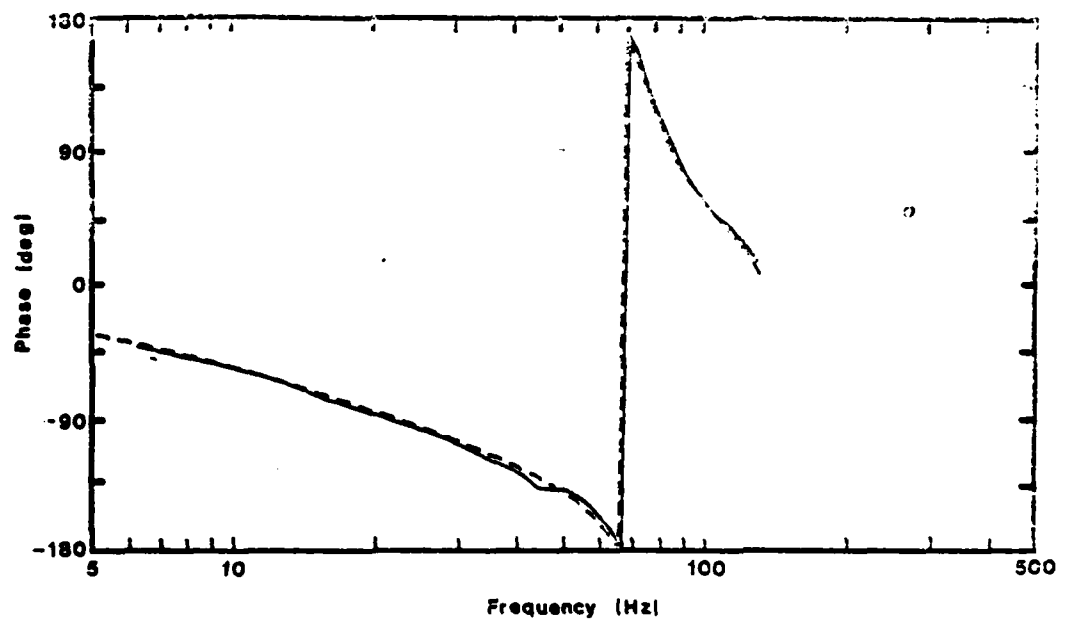
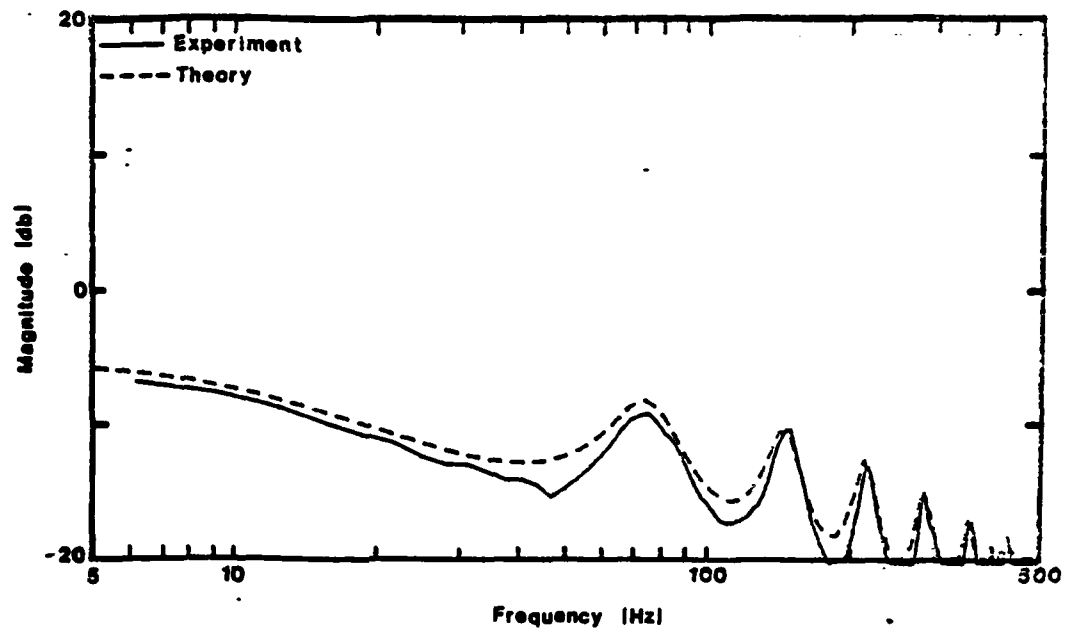
Data Set 152. Line with Source Impedance and Load Impedance  
 ( $\ell = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $a = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



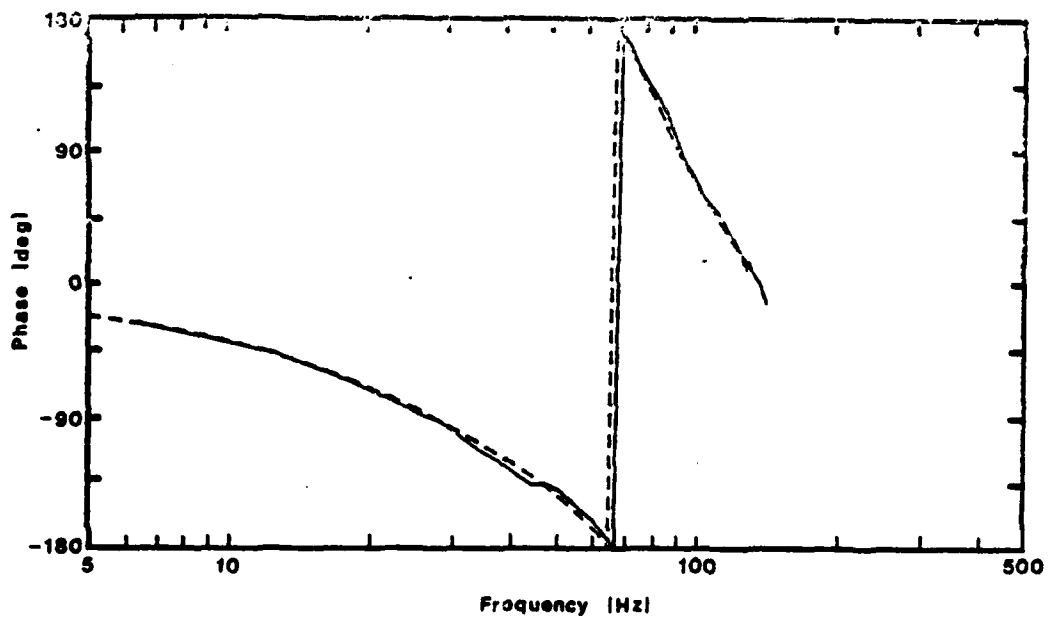
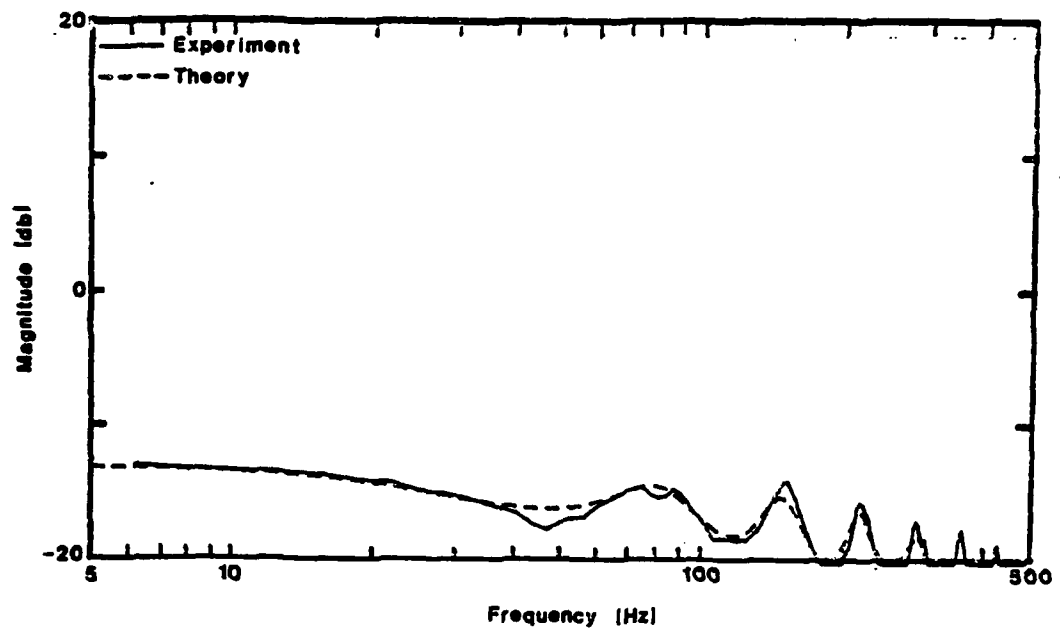
Data Set 153. Line with Source Impedance and Load Impedance  
 ( $\lambda = 4.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\lambda = 315$  mm,  $d = 2.37$  mm)



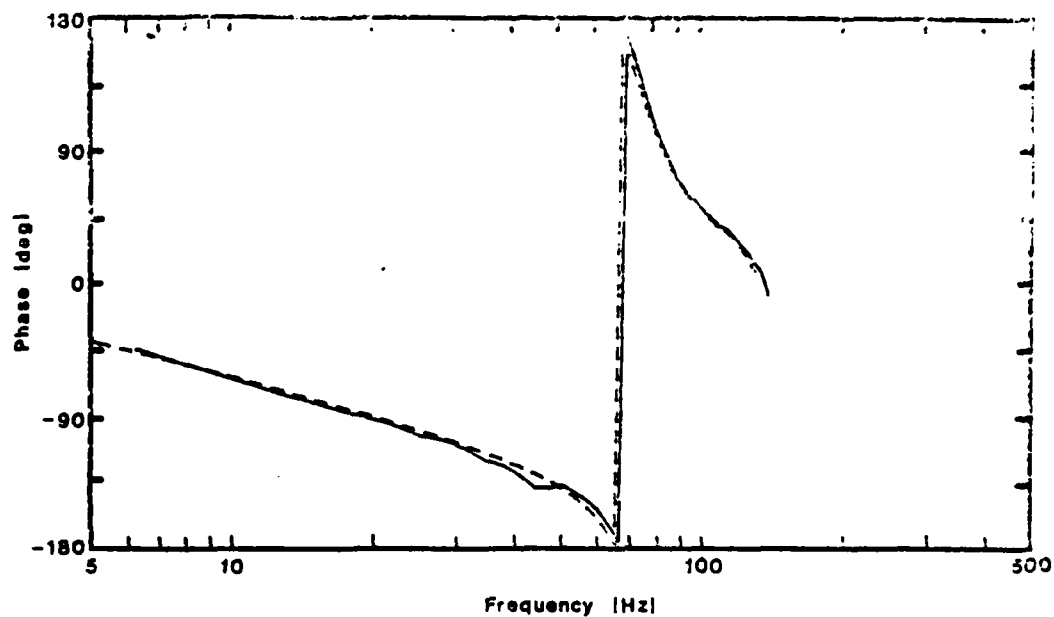
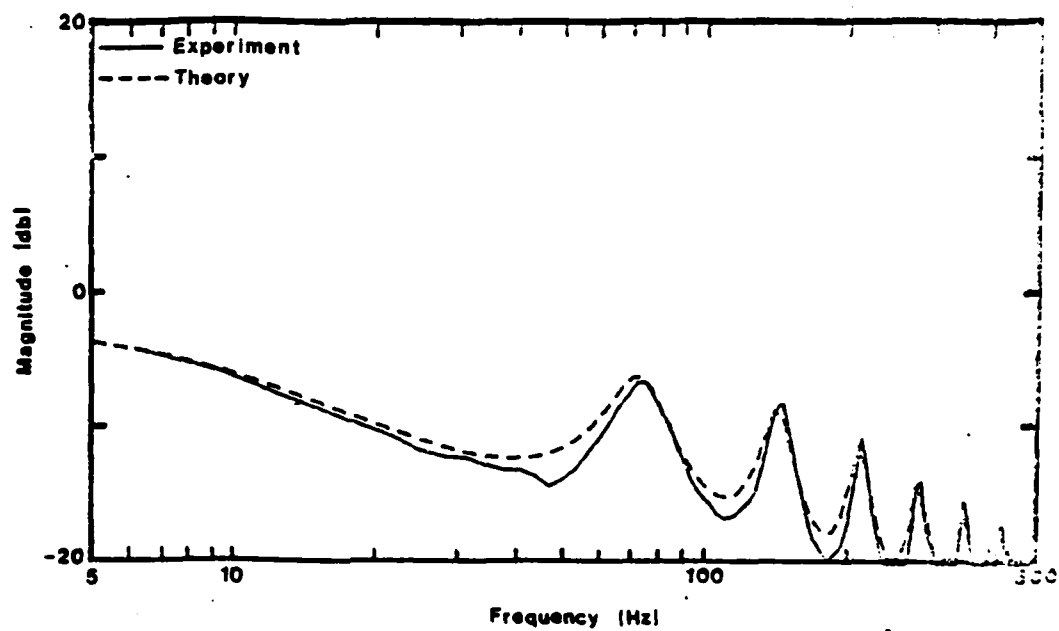
Data Set 154. Line with Source Impedance and Load Impedance  
 ( $l = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #1,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $l = 24.2$  mm,  $d = .427$  mm)



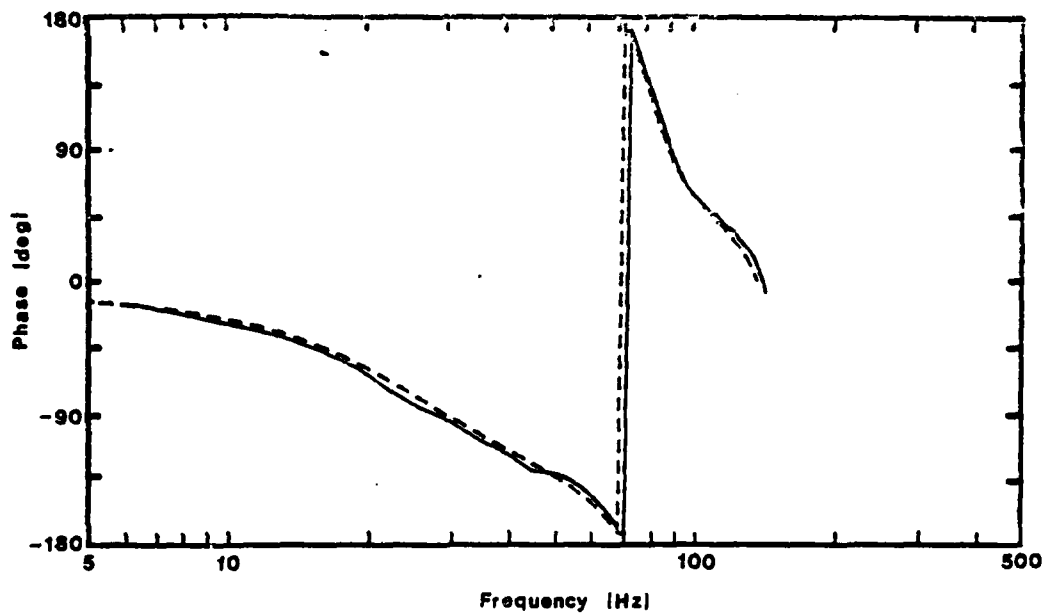
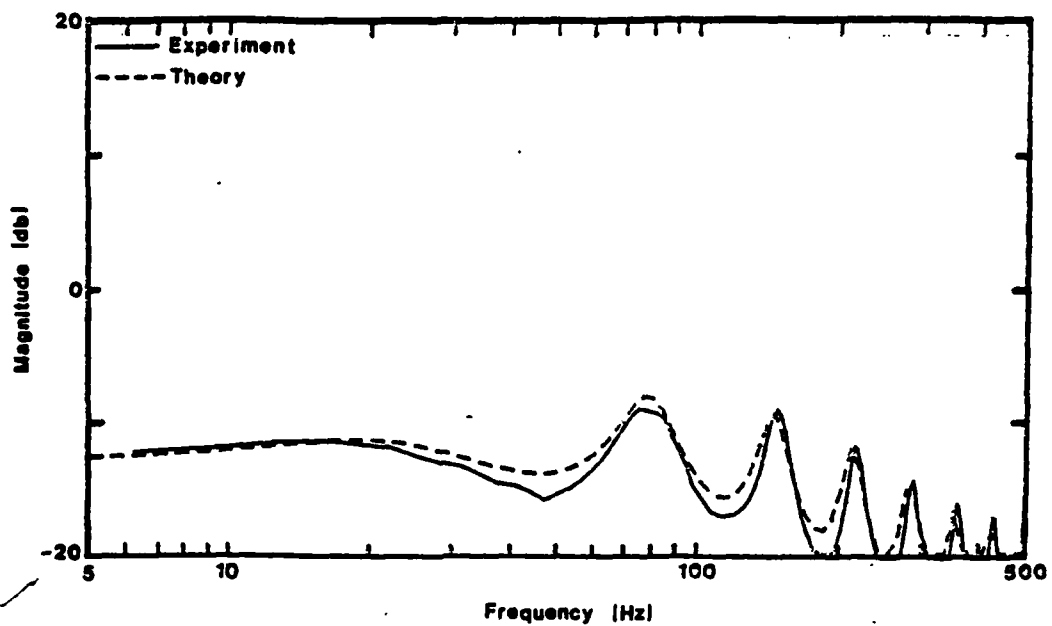
Data Set 155. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #4,  $\ell = 50$  mm,  $d = .716$  mm)



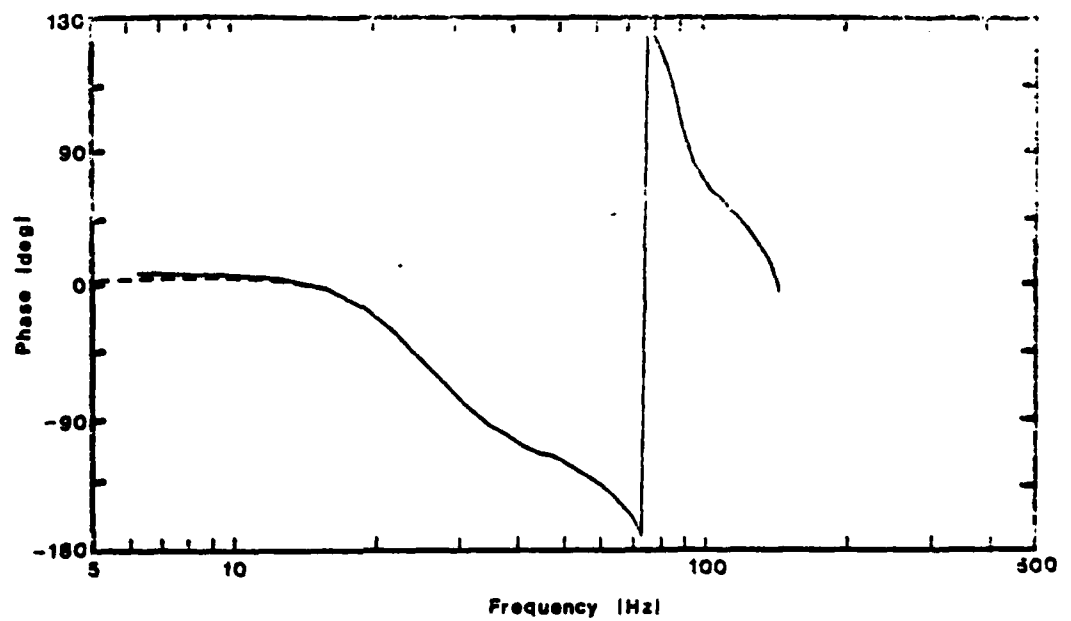
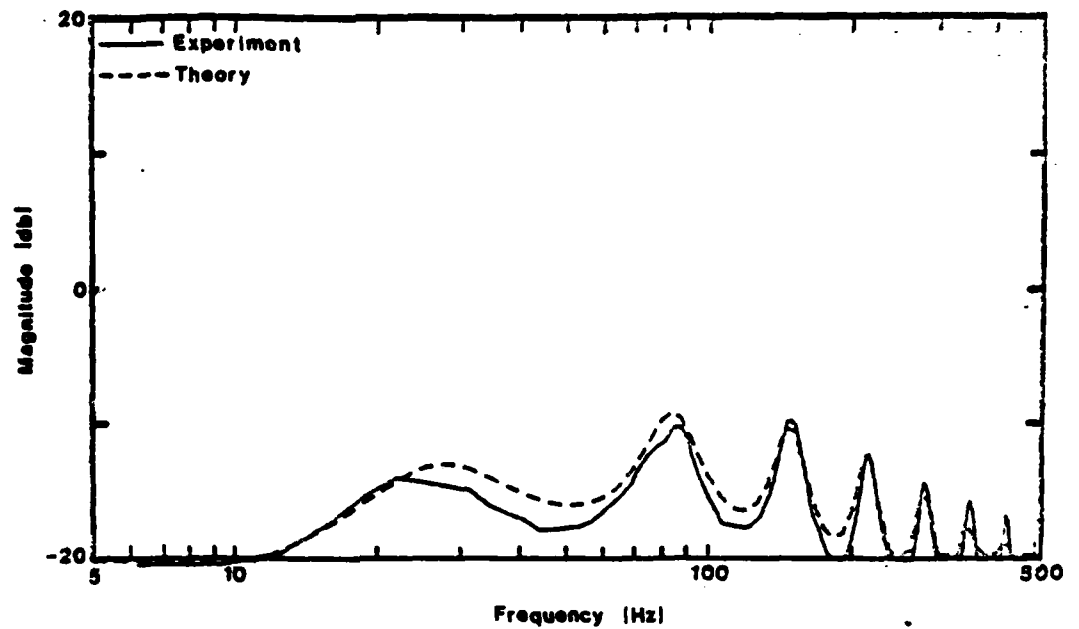
Data Set 156. Line with Source Impedance and Load Impedance  
 ( $l = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #1,  $l = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $l = 52$  mm,  $d = .716$  mm)



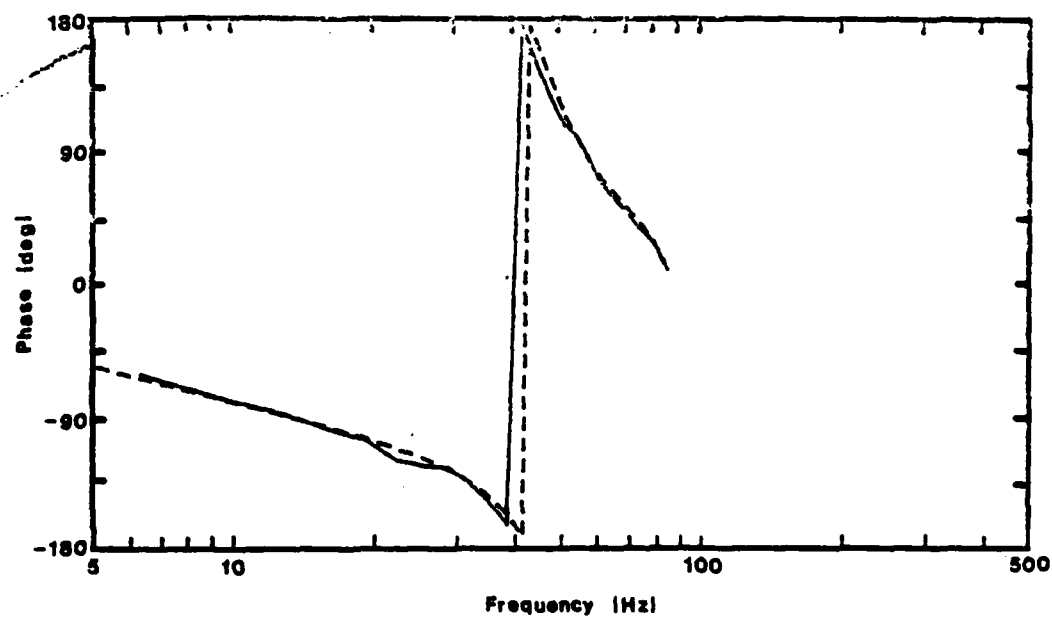
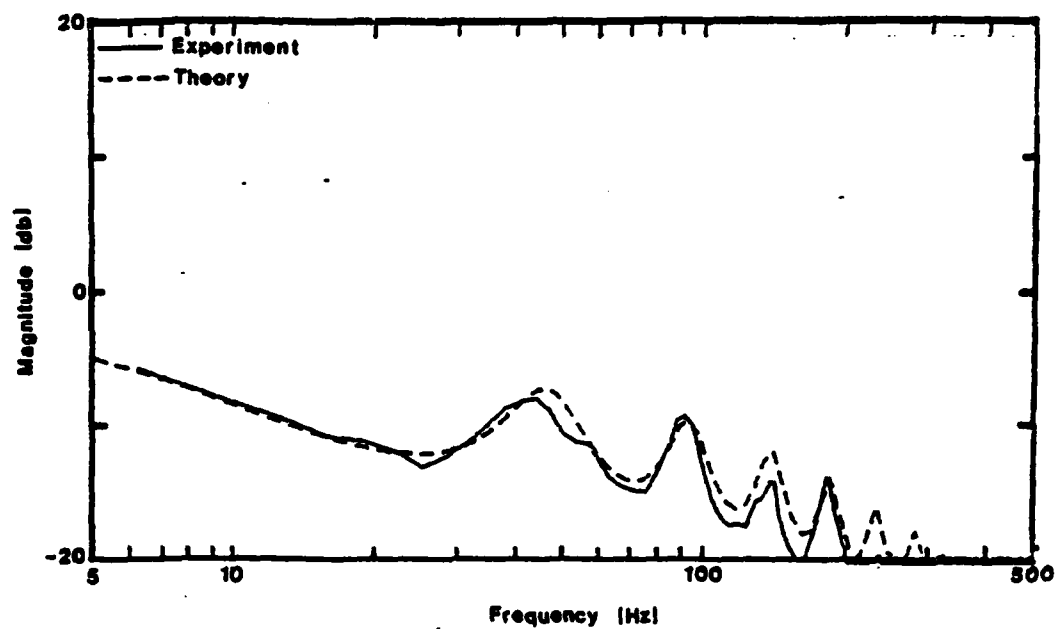
Data Set 157. Line with Source Impedance and Load Impedance  
 ( $\lambda = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



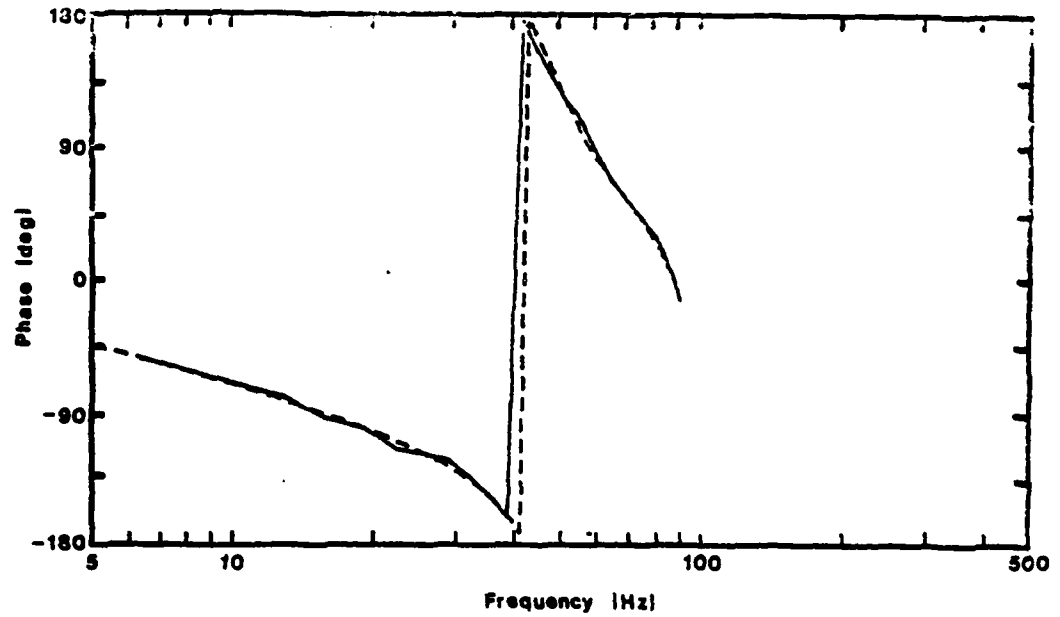
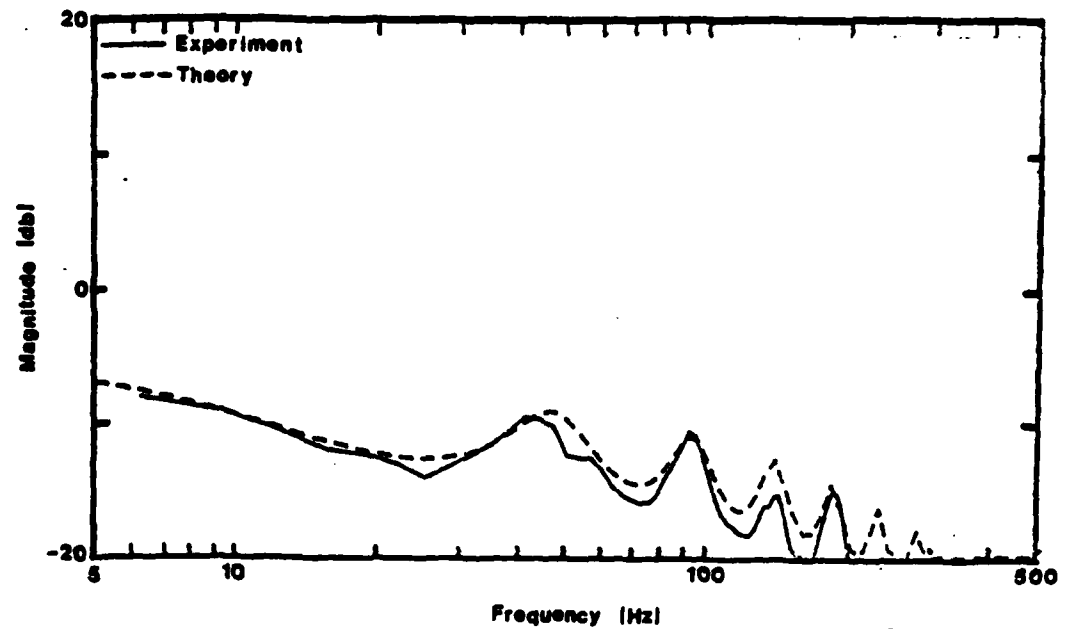
Data Set 158. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\ell = 290$  mm,  $d = 1.63$  mm)



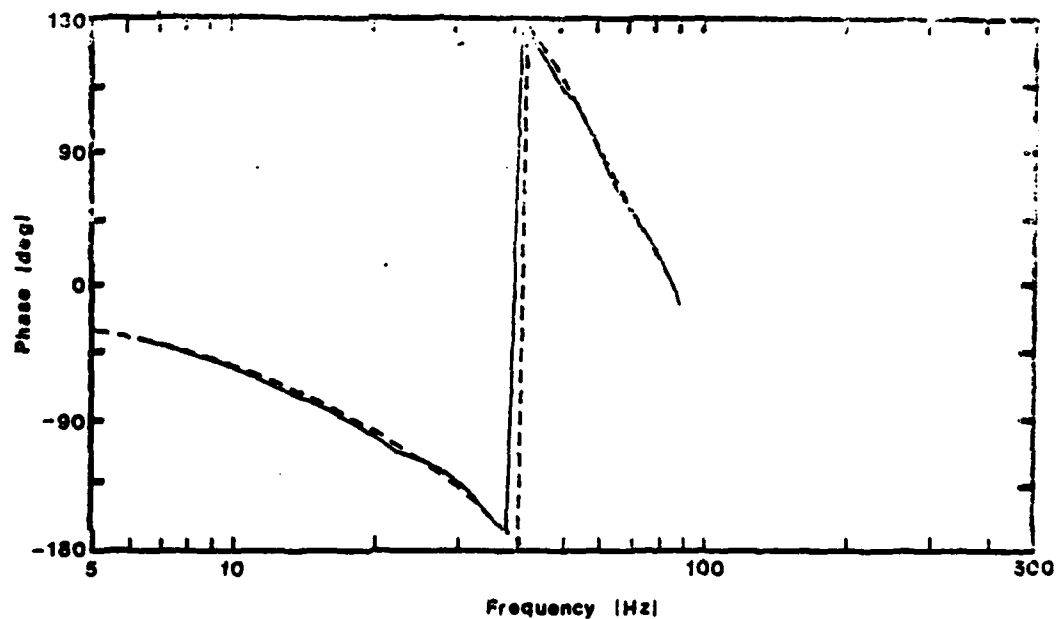
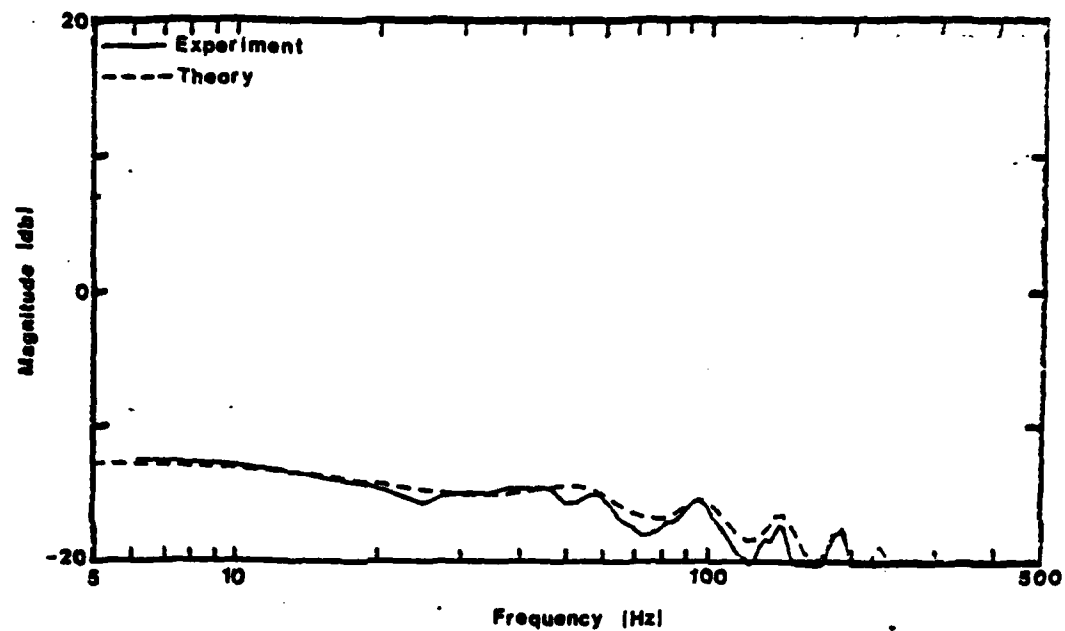
Data Set 159. Line with Source Impedance and Load Impedance  
 ( $\ell = 9.6$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)



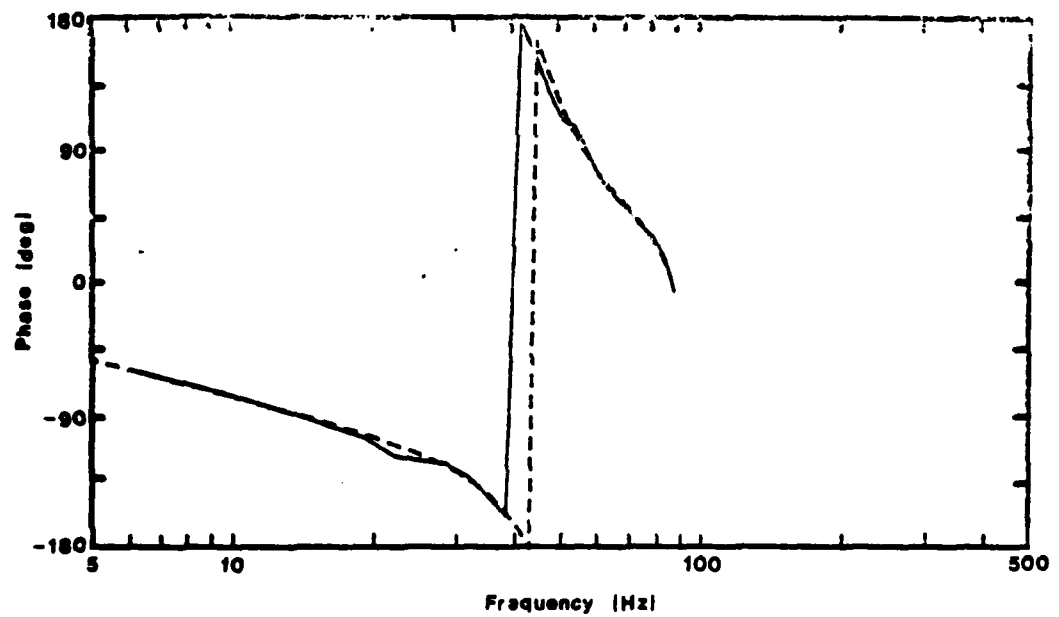
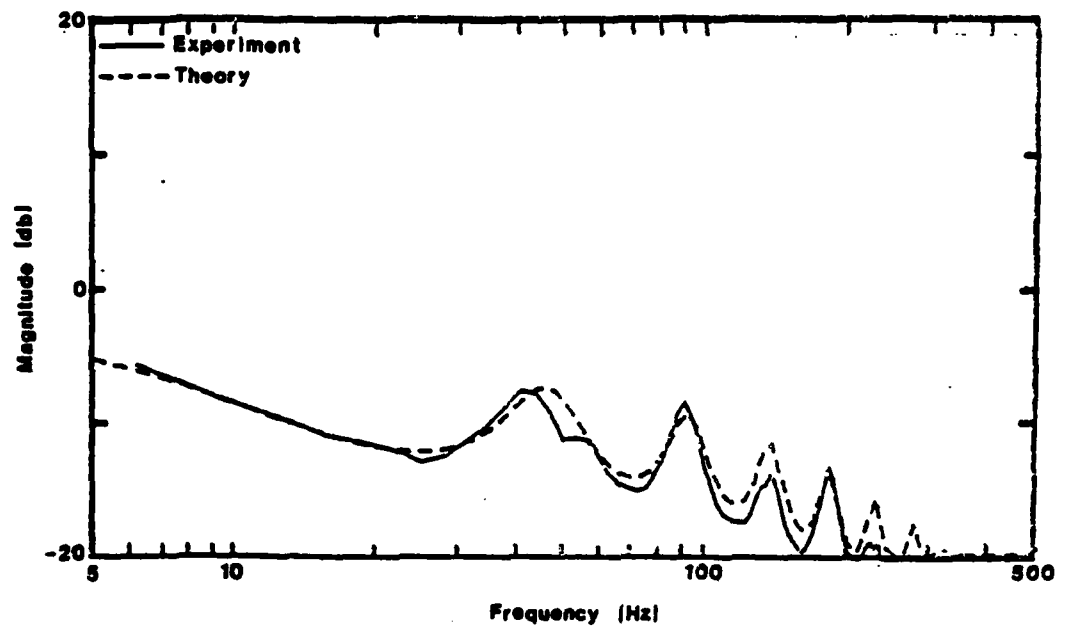
Data Set 160. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #3,  $\ell = 24.2$  mm,  $d = .427$  mm)



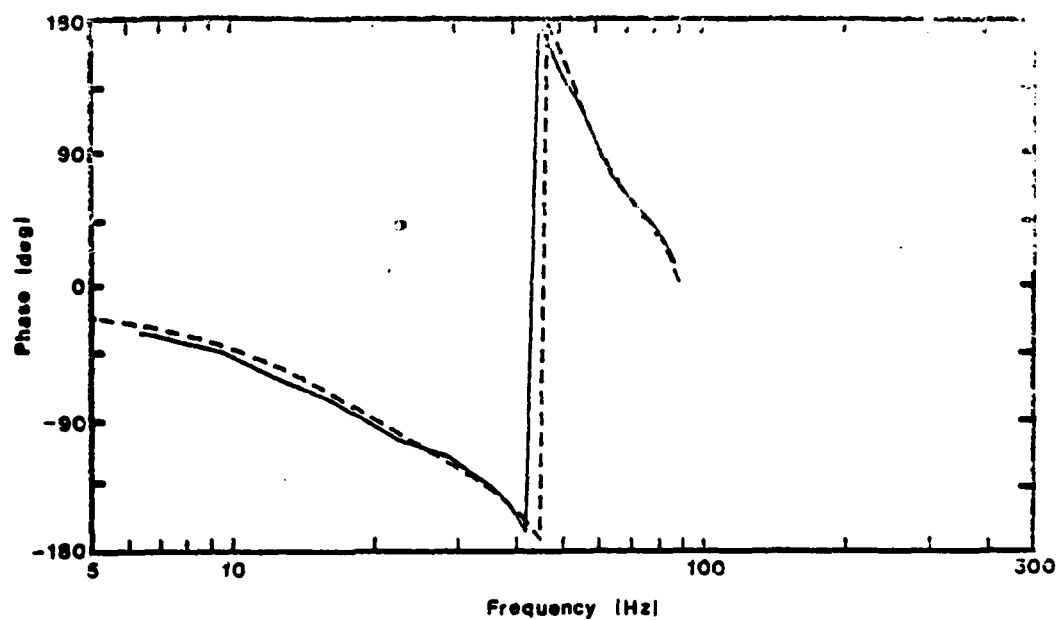
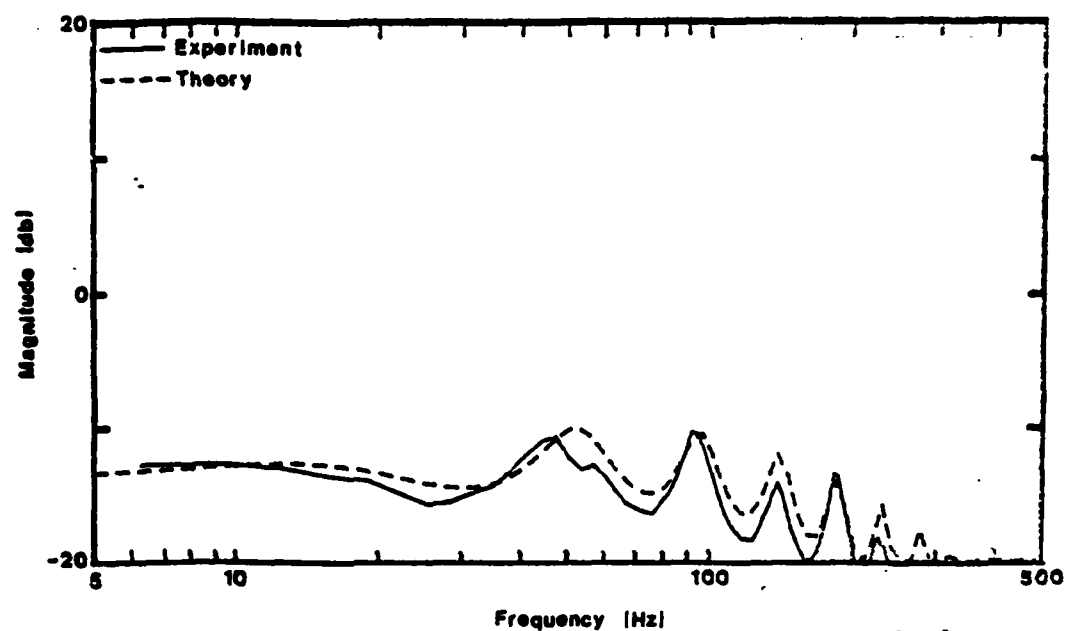
Data Set 161. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8\text{m}$ ,  $d = 7.6\text{ mm}$ ; Source: Resistor #1,  $\ell = 53\text{ mm}$ ,  
 $d = .716\text{ mm}$ ; Load: Resistor #4,  $\ell = 50\text{ mm}$ ,  $d = .716\text{ mm}$ )



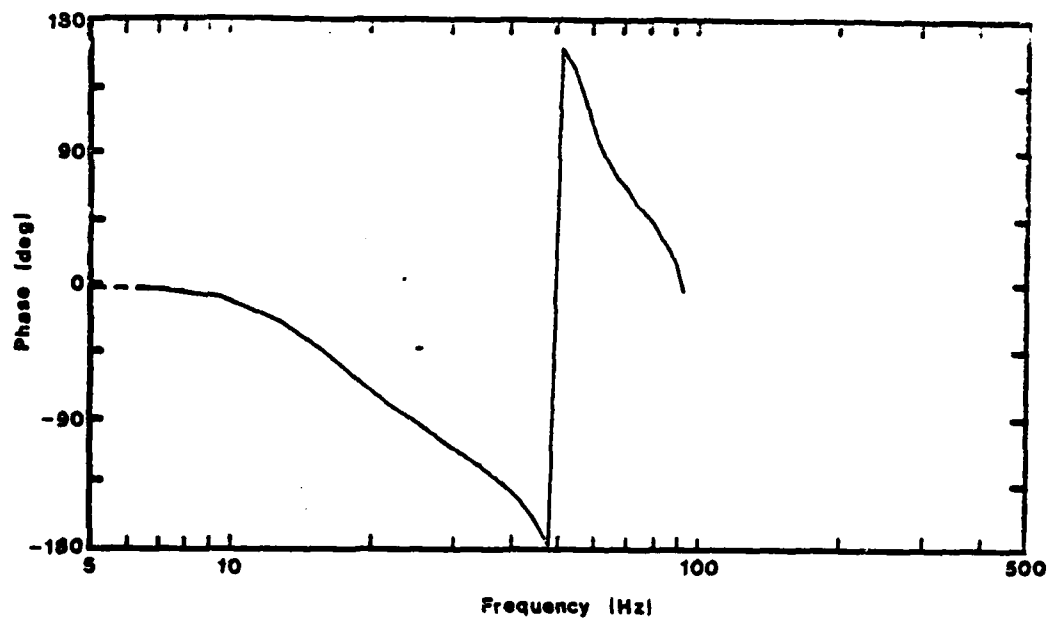
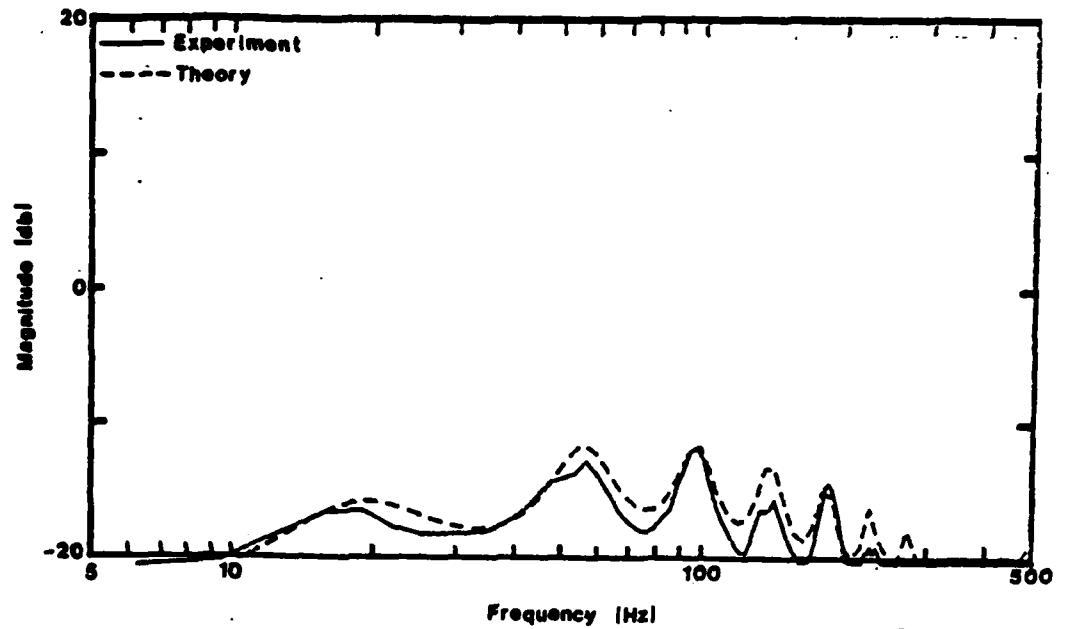
Data Set 162. Line with Source Impedance and Load Impedance  
 ( $\ell = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #5, 4 tubes,  $\ell = 52$  mm,  $d = .716$  mm)



Data Set 163. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #6,  $\lambda = 297$  mm,  $d = .88$  mm)



Data Set 164. Line with Source Impedance and Load Impedance  
 ( $\lambda = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\lambda = 53$  mm,  
 $d = .716$  mm; Load: Resistor #7,  $\lambda = 290$  mm,  $d = 1.63$  mm)



Data Set 165. Line with Source Impedance and Load Impedance  
( $\ell = 14.8$  m,  $d = 7.6$  mm; Source: Resistor #1,  $\ell = 53$  mm,  
 $d = .716$  mm; Load: Resistor #8,  $\ell = 315$  mm,  $d = 2.37$  mm)

NOMENCLATURE AND NOTATION

$a$  = Numerator coefficients for Bessel function ratio

$b$  = Denominator coefficients for Bessel function ratio

$B_r$  = Bessel Function ratio

$c_0$  = Speed of sound

$C$  = Capacitance

$d$  = Line internal diameter

$D$  = Differential operator =  $\frac{d}{dt}$

$\bar{D}_c = \frac{D}{\omega_c}$

$\bar{D}_v = \frac{D}{\omega_v}$

$E$  = Young's Modulus

$j = \sqrt{-1}$

$J_0, J_1$  = Bessel Functions

$l$  = Line length

$L$  = Inductance

$P$  = Pressure

$Q$  = Volume flow rate

$R$  = Resistance

$Z$  = Impedance

$\beta$  = Bulk modulus

$\gamma$  = Specific heat ratio

$\Gamma$  = Propagation operator

$\zeta$  = Damping ratio

$\mu$  = Absolute viscosity

$\nu$  = Kinematic viscosity

$\rho$  = Fluid density

$\omega_v$  = Viscous frequency

$\omega_c$  = Line Characteristic frequency

$\sigma$  = Prandtl number

$\omega$  = Frequency

Subscripts:

a = Line inlet

b = Line outlet

c = Characteristic of line

m = Index

L = load

S = Source

Units:

kPa =  $\text{kN/m}^2$

Lohm =  $\text{kN}\cdot\text{s}/\text{m}^5$  = resistive impedance

MLohm =  $10^6$  Lohm

Farad =  $\text{m}^5/\text{kN}$  = capacitance

pFarad =  $10^{-12}$  Farad

Henry =  $\text{kN}\cdot\text{s}^2/\text{m}^5$  = inductance

MHenry =  $10^6$  Henry

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